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This report presents the results of an analysis of existing data from various sources on the removal of radium from potable water supplies by lime-soda softening, ion exchange, and reverse osmosis treatment methods. Removal efficiency models are used to estimate the capital and annual operating and maintenance costs for each water treatment process over a wide range of raw water quality, raw water radium, and population conditions.

The radiological consequences of common methods of waste sludge and brine disposal are discussed and waste volumes and activity levels of radium in waste streams are estimated. The costs of ultimate disposal of the waste streams produced by each process are estimated over the same raw water quality and population ranges used to determine treatment costs.

This report is intended as a guide for planners and water utility personnel in areas where the radium activity of potable water sources exceeds the limits set by EPA Drinking Water Regulations.

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COSTS OF RADIUM REMOVAL FROM POTABLE WATER SUPPLIES

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

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This report estimates the capital and operating costs of removing radium from public water supplies by lime-soda softening, ion exchange, and reverse osmosis treatment methods. Cost of waste stream handling and ultimate disposal are considered as well as treatment costs.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This report presents the results of an analysis of existing data from various sources on the removal of radium from potable water supplies by lime-soda softening, ion exchange, and reverse osmosis treatment methods. Removal efficiency models are proposed for each process based on the compiled data. These models are used to estimate the capital and annual operating and maintenance costs for each water treatment process over a wide range of raw water quality, raw water radium, and population conditions.

The radiological consequences of common methods of waste sludge and brine disposal are discussed and waste volumes and activity levels of radium in waste streams are estimated. The costs of ultimate disposal of the waste streams produced by each process are estimated over the same raw water quality and population ranges used to determine treatment costs.

This report is intended as a guide for planners and water utility personnel in areas where the radium activity of potable water sources exceeds the limits set by EPA Drinking Water Regulations.

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SECTION I

INTRODUCTION

PURPOSE OF REPORT

The purpose of this report is three-fold:

(1) to assemble existing data on the removal of radium from public water supplies;

(2) to determine the costs of reducing radium to the proposed interim standard of 5.0 pCi/l, including both capital and operating costs for treatment, waste stream handling, and ultimate waste disposal; and

(3) to identify areas in which further research will be required in order to assist utilities in implementing the proposed interim standard.

RADIUM IN WATER SUPPLIES

Radium is the element with atomic number eighty-eight and is the most massive member of the alkaline earth metals or group IIA of the Periodic Table. Other members of the alkaline earth metals are beryllium, magnesium, calcium, strontium, and barium; these have a chemical behavior similar to radium. Thus, radium will be transported in a manner similar to magnesium and calcium; also, their destinations will be similar. For example, ingested calcium and radium concentrate in the bones of humans.[1]

Radium is present in water as a naturally occurring element, primarily in groundwaters and to a lesser extent in surface waters. Studies by Hursh[2] on the water supply sources of 41 cities in the U.S. showed that the average ^{226}Ra concentration of those municipal water supplies which utilized surface sources was less than 0.3 pCi/l, ranging from 0.002 to 3.7 pCi/l. Numerous studies on groundwater supplies in areas of radium bearing deposits have demonstrated ^{226}Ra concentrations in the range of about 0.5 pCi/l to concentrations exceeding 50 pCi/l. The EPA[3] has estimated that as many as 500 public water supplies exceed the 5.0 pCi/l radium concentration.

Elevated levels of radium in groundwaters are thought to be caused by the leaching of radium from radium-bearing rock strata into the deep sandstone aquifers in Iowa and Illinois, and by leaching of radium from phosphate-rock deposits found in parts of Florida into the Floridan Aquifer. Elevated radium levels have also been associated with surface run-off water in the vicinity of uranium-rich deposits in Colorado and New Mexico.

Radium and other alkaline earth metals are not necessarily found in the same place or in the same abundance. This is because radium that is found in nature is a daughter or decay product in all three of the naturally occurring radioactive series, each series eventually decaying to a stable isotope of lead. For example, the ^{226}Ra isotope is the fifth series progeny of ^{238}U (half-life, 4.51 billion years). Similarly, ^{228}Ra and ^{224}Ra are daughters and the fourth series progeny of ^{232}Th (half-life, 14.1 billion years). Both ^{224}Ra and the ^{223}Ra from the ^{235}U chain are of little importance because of their short half-lives, 3.64 days and 11.43 days, respectively. Because of half-life differences in the parent, all daughters in equilibrium with a microgram of ^{238}U will be at 0.334 picocuries. Similarly, all daughters in equilibrium with a microgram of ^{232}Th will be 0.111 picocuries.

The importance and concentration of ^{226}Ra and ^{228}Ra in groundwaters can be intuitively understood by simple examination of the distribution of uranium and thorium in underground strata. Sedimentary rocks such as sandstones, shales, and limestones have average uranium concentrations of 1.2-1.3 μg/g, whereas thorium concentrations vary from 1.3 μg/g in limestones to 6 μg/g in sandstones to 10 μg/g in shales. Thus, for example, a sandstone with 1.3 μg/g of uranium and 6 μg/g of thorium would contain 0.434 pCi/g of uranium daughters at equilibrium. It should be evident that radium dissolved out of sedimentary rocks could be about equally divided between ^{226}Ra and ^{228}Ra. However, if transport is involved and the time scale is on the order of tens of years, the ^{228}Ra contribution would be greatly reduced by decay because of its 5.75 year half-life.

HEALTH EFFECTS OF INGESTED RADIUM

From the point of view of ionizing radiation delivered to man, the isotopes ^{226}Ra and ^{228}Ra have about equal significance.[4] ^{226}Ra, a member of the uranium series, is an alpha particle emitter that decays with a half-life of 1622 years, to ^{222}Rn, a noble gas with a half-life of 3.82 days. The decay of ^{222}Rn is followed by a number of short-lived alpha and beta emitting daughters. ^{228}Ra is a member of the thorium series. It is a β-particle emitter with a half-life of 5.75 years and decays through ^{228}Ac to the alpha emitting ^{228}Th. ^{228}Th decays through a series of short-lived alpha and beta transitions to ^{208}Pb.

Both ^{226}Ra and ^{228}Ra concentrate primarily in the bones and skeletal tissues and have been linked to increased human fatalities due to malignant neoplasma[5], leukemia[6] and other carcinomas[6].

In 1961, the Federal Radiation Council published Radiation Protection Guides (RPG) which set guidelines for total intake (from all sources, including food and water) for ^{226}Ra as follows[7]:

TABLE 1. RADIATION PROTECTION STANDARDS RECOMMENDED BY THE FEDERAL RADIATION COUNCIL

Nuclide	Intake levels, pCi/day		
	Range I*	Range II†	Range III‡
^{226}Ra	0-2	2-20	20-200

* Calculations based on source information. Surveillance adequate to confirm calculations.

† Surveillance adequate to demonstrate levels. Control at source to avoid excess exposure as levels increase to top of Range II. Intakes do not exceed the recommended Radiation Protection Guides (RPG).

‡ Surveillance to check effect of control actions. Control designed to reduce levels to Range II or lower. Intakes in Range III will result in exposures exceeding RPG if continued for a sufficient period.

STANDARDS FOR RADIUM IN DRINKING WATER

The 1962 U. S. Public Health Service Drinking Water Standards listed a maximum concentration of ^{226}Ra in water used on interstate carriers of 3.0 pCi/l[8]. Recognizing the health effects of ingestion of both ^{226}Ra and ^{228}Ra, the U.S. Environmental Protection Agency has published Interim Primary Drinking Water Regulations[9], which include limits on radium as listed below:

Radionuclides	Maximum Contaminant Level
^{226}Ra + ^{228}Ra	5 pCi/l
Gross Alpha Activity (including ^{226}Ra but excluding radon and uranium)	15 pCi/l

If gross alpha activity exceeds 2 pCi/l in those locations where ^{228}Ra may be present in drinking water, ^{226}Ra analysis is required.

If ^{226}Ra exceeds 3 pCi/l, analysis for ^{228}Ra is required. Recommended analytical techniques for each radionuclide of interest in the Interim Standards are published in Interim Radiochemical Methodology for Drinking Water, Environmental Monitoring and Support Laboratory, EPA-600/4-75-008, U.S.E.P.A., Cincinnati, Ohio 45268[10].

REMOVAL OF RADIUM FROM WATER

The water treatment plant is the point of control between radium dissolved or suspended in raw water supplies and the consumer. In order to meet the proposed interim standard of 5 pCi/l in the most cost-effective manner, it is important to understand how the treatment process affects the level of radium in potable water.

The major problem of concern in public water supplies is soluble radium in groundwater supplies. Soluble radium exists in water as a divalent ion, similar in chemical behavior to calcium and magnesium. Softening treatment methods have been shown to be effective in removing 59-99 percent of dissolved radium, as have membrane desalting methods. Coagulation without softening may remove up to 25 percent of radium, however, the results are variable and difficult to control.

The three methods selected for analysis in this report are:

(1) Lime and Lime-Soda Softening

(2) Ion Exchange Softening

(3) Reverse Osmosis

Radium removal efficiencies and associated operating data from water treatment plants in Illinois, Iowa and Florida have been compiled and analyzed in this report. Removal efficiencies for each of the three treatment methods, generalized plant flow diagrams, waste stream handling and disposal methods, as well as associated costs of treatment and waste disposal are reported for each type of plant in following sections of this report.

SECTION II

CONCLUSIONS

GENERAL

No statistically significant correlation was found between raw water radium activity levels and other raw water quality parameters investigated, although a trend toward significance was noted between radium and the heavy metals, iron, barium, and boron.

LIME-SODA SOFTENING

Radium removal efficiencies of the six lime-soda softening plants investigated varied from 59-96 percent removal, averaging 80 percent. Radium removal was found to vary with removal of total hardness according to a nonlinear relationship.

The majority of the radium activity removed during lime-soda treatment appears in the waste sludge. The activity in the dry sludge approaches 10^5 pCi/kg and special consideration must be given to safe disposal of the contaminated sludge. Disposal of filter backwash water poses no particular problem since the activity levels in this waste stream were found to be only slightly higher than levels found in the raw water.

Lime-soda softening was shown to be a cost-effective method of treatment for reducing radium levels to meet Federal Drinking Water Standards, particularly for plants larger than 10 MGD capacity.

ION EXCHANGE

Investigation of radium removal at eight ion exchange plants demonstrated that 95 percent or greater efficiencies can be expected from a well-operated plant. Plants operated past the normal breakthrough point or plants which were incompletely regenerating their exchange media continued to remove 65-85 percent of the influent radium activity.

The majority of radium activity removed in the ion exchange process appears in the regenerant brine effluent at levels approaching 10^3 pCi/l.

Approximately 9 percent of the radium activity remains in the exchange medium and is not regenerated by normal means. Disposal methods for spent brine may more often be limited by considerations of salinity rather than radium activity levels.

Ion exchange was shown to be a cost-effective method of reducing radium levels to meet EPA Drinking Water Regulations, particularly at plant capacities below 10 MGD.

REVERSE OSMOSIS

Investigation of radium removal at two reverse osmosis plants demonstrated that 95 percent or greater efficiencies can be expected from a well-operated plant. Radium activity levels in reject brine from reverse osmosis plants are lower than those of ion exchange plants, however, reject brine volumes are much higher. Disposal techniques may more often be limited by considerations of salinity rather than radium activity levels.

Costs of reverse osmosis treatment were higher than for the other methods investigated and it is expected that reverse osmosis will be limited to applications in which the raw water is quite brackish or where the raw water radium is extremely high.

SECTION III

RECOMMENDATIONS

The radium removal models presented in this report are based on radium analyses of raw and finished water taken during normal plant operation. The radium removal efficiencies reported are incident to operation of the plant to meet other water quality criteria. The present data, therefore, do not reflect any attempt to optimize radium removal by relating radium removal efficiency with other operating parameters, such as pH of treatment, detention time in clarification during lime-soda softening, optimum brine concentration of regenerating salt in ion exchange, etc. This is particularly true for the lime-soda softening process. The range of radium removal efficiencies of the lime-soda plants studied in this report ranged from 59-96 percent. Pilot plant or full scale plant testing could establish the optimum operating characteristics for consistent removal of radium nearer the upper limit of the range.

Ion exchange and reverse osmosis are better defined in terms of relating removal efficiency of radium to removal of total hardness or total solids. There are, however, some unresolved questions which further study could help to answer.

In ion exchange, for instance, what are the long term effects of radium upon the media? Is the radium completely regenerated from the media or is there a build-up of radioactivity? If there is a build-up of radioactivity, can it be periodically removed by regeneration with acid or other chemicals?

Since the radium removal model for reverse osmosis was formulated from the operating data from only two plants, more full scale studies of this process should be conducted before its use in radium removal is completely endorsed.

Radiological implications of waste stream disposal were arrived at in this report by calculating activities developed from a mass balance of radium reported by investigators in radium removal studies of the three treatment processes. On-site investigations at landfills, sludge lagoons, brine holding ponds, reclaimed land, and other sites where radium-rich wastes have been disposed of for long periods of time should be carefully conducted to determine the accuracy of the generalizations made in this report.

SECTION IV

PROBLEMS OF ULTRA LOW-LEVEL RADIOACTIVE WASTES

In the evolution of the nuclear industry a convenient rule-of-thumb classification of radioactive wastes developed. High level radioactive wastes were those that contained curies per liter, intermediate level wastes were those that contained millicuries per liter, and low level wastes were those that contained microcuries per liter. It was very obvious that high-level wastes needed very special treatment, normally in the form of concentration before complete containment. These wastes were often handled at a site remote from where they were generated. Historically, intermediate-level wastes may have received treatment of some form at the site of production and often the underlying principle was delay for decay. Lastly, low-level wastes were "treated" by the principal of dilute and dispense. Often the transport phenomena was mathematically considered in order to predict the final environmental concentration.

Wastes which contained activites on the order of nanocuries per liter or less were considered ultra-low level wastes and often were released without consideration. These rules-of-thumb and treatment principals have subsequently experienced changes in philosophy.

Because each radioactive isotope has a unique combination of radiological properties and because the effects on man are a function of these properties, standards evolved for each isotope. For example, the International Committee for Radiation Protection (ICRP) gave maximum permissible concentrations (MPC) for soluble and insoluble ^{226}Ra for both occupational and non-occupational groups. For a 168-hour week, those exposed as a result of their occupations were permitted 100 pCi/l for soluble ^{226}Ra; correspondingly, the general population was allowed 1/30 of this concentration; i.e. 33 pCi/l for soluble ^{226}Ra.

The American Standards Association (ASA) would classify wastes into four classes which are based on MPC and maximum permissible quarterly intake (MPQI). Their concentrations for both the soluble ^{226}Ra and a solid matrix with ^{226}Ra are the following: Class A, liquid $\leq$ 3.3 pCi/l and solid $\leq$ 6.7 x 10^2 pCi/kg; Class B, liquid > 3.3 pCi/l but $\leq$ 100 pCi/l and solid > 6.7 x 10^2 pCi/kg but $\leq$ 2 x 10^4 pCi/kg; Class C, liquid > 100 pCi/l but $\leq$ 1 Ci/l and solid > 2 x 10^4 pCi/kg but $\leq$ 200 Ci/kg; Class D, liquid > 1 Ci/l and solid > 200 Ci/kg. It is notable that radium wastes do not fit the rule-of-thumb classification. The ASA classification would place any concentration of radium into some class.

Preparation of both potable water from groundwater in sections of Iowa and Illinois and fertilizer from phosphate-rich regions of Florida are prime examples of the potential for generating ultra-low radium-containing wastes. These operations produce wastes between the range of nanocuries per liter and picocuries per liter and would often be Class B or Class C wastes. Even if concentrated, most would not exceed Class C. More importantly, however, the natural matrix from which these wastes are generated are originally Class B Wastes! Therefore, the simple act of pumping deep-well water for irrigation in some areas of Iowa and Illinois would be considered as releasing a Class B waste. The radium problem is further confounded by the ubiquitous and variable nature of radium in almost all environmental media. If many of the wastes in this study can experience a dilution factor of 100 upon their release to the environment, they would essentially be at background concentrations.

Wastes which are not radioactive are often a combination of organic and inorganic material. The organic material is catabolized by living organisms unless man converts it to carbon dioxide and water by combustion. The inorganic material, though also utilized by living organisms, is subject to other processes such as chemical changes and weathering. When volume is used as a measurement criteria, such wastes are usually retained in the biosphere even though many of the original constituents may have been obtained from deep within the earth. A prime example of such wastes would be those domestic solid wastes that end up in sanitary landfills. Such wastes are thought of as "disposed" since they require little or no maintenance and little if any monitoring is performed unless groundwater is easily contaminated.

However, radioactive wastes, being essentially all inorganic, are never thought to be "disposed" of under equivalent conditions because of their radioactivity. Factors which necessitate a different philosophy when dealing with radioactive wastes include the following: (1) the "life times" during which they can exert their deleterious effects are a function only of time, (2) the "life times" are incapable of being modified (except by artificially induced transmutation), (3) the long "life time" of many of the radionuclides, (4) the ever-changing chemical states resulting from natural transmutations or decay, (5) the possible change of physical state, as for example in solid ^{226}Ra to gaseous ^{222}Rn, and (6) the biological effects. For these reasons radioactive wastes necessitate long-term protection over and above that normally used for organic and other wastes.

Concentration and confinement of ultra-low level effluents are desirable if there were no considerations other than safety. This would be true disposal. Disposal is the best means for ensuring long-term protection since by definition it is not only for an effective infinite time but also provides for no interaction with the biosphere. Disposal requires neither maintenance nor legal controls once accomplished; it is strategy, not a tactic. An ideal disposal method would be by returning the radioactive matrix to the general area from which it was obtained; this is especially true if the radioactive waste matrix is chemically similar to the original matrix. Returning a backwash to an aquifer (possibly the original one) is such an example.

As would be expected, the lower the activity level of wastes, usually the more there is of it. The expense of concentrating large volumes of material can quickly become excessive and the cost-benefit equation begins to be out of balance.

The second alternative for ultra-low level waste is delay for decay. In general these are surface facilities such as evaporation lagoons. When the radioactive waste has a short half-life this is an excellent solution. For radium, the expected lifetime of such facilites is insignificant in comparison to that of the radionuclide. Ultra low-level effluents released from storage facilities to the uncontrolled portion of the biosphere may, through fundamental natural processes of redistribution and transformation, be physically or biologically accumulated to undesirable levels in the environment. Delay for decay will usually imply some type of environmental monitoring and this expense must be factored into the cost-benefit equation.

Dilution and dispersion of ultra low-level radium wastes into either the aquatic or terrestrial environment must remain an alternative. Radium is rather widespread in nature,and many of man's endeavors, such as the nuclear fuel cycle, release radium. When the diluted waste will not make a significant impact on the environmental concentration or the ultimate consequence of an elevated environmental concentration is expected to be insignificant, then the cost (risk) - benefit equation would suggest using this least expensive procedure. Of course, if these radioactive substances are to remain in the biosphere in diluted form, their transport pathways and biological effects should be well understood.

The aforementioned discussion points out the dilemma of radium-containing ultra low-level wastes generated from potable water treatment facilities. The best solution from a radiological health point of view is concentration and containment, however, the expense involved for a water treatment facility will likely be inordinate in comparison to the value of the product.

Delay for decay will probably not be acceptable from either cost consideration or protection. The radium half-life is too long, the potential for eventual release in a rather concentrated form is high. Monitoring will be required.

Dilution and dispersion may be the only alternative that has a small enough economic impact to be considered. However, the radiological health implications will have to be seriously examined. Some important factors are (1) the natural or background concentrations of radium in the dispersing medium, (2) the assimilative capacity and volume of the dispersing medium, (3) the immediate utilization of the dispersing medium, (4) the potential for reconcentration, transport or other environmental changes, and (5) the future use of the dispersing media or other locations where the waste may eventually reside. Potential for transport to man is the key issue. The variables are almost too numerous to list but include aspects of geography, geology, land use, hydrology, etc.

One can conclude that a "best" solution to the waste problem generated by water treatment plants handling radium bearing wastes does not exist. The solution for each plant may lie in an environmental analysis where the complete benefit versus costs (risk) balance is evaluated. This should include an analysis of alternatives to the use of the groundwater.

Bottled water for consumption is one alternative. Surface waters resources should be examined. It should be pointed out that surface waters have a great potential for contamination by other man-made or natural hazards, some of which are as relatively carcinogenic as the radium concentrations considered in this report. The final analysis should consider all these aspects.

SECTION V

PROCEDURE AND COST BASES

ASSUMPTIONS AND PARAMETERS

Source of Data

Although it has been known for many years that several geographical areas of the United States have levels of radium in their raw and finished water supplies which exceed the 1962 USPHS limit for ^{226}Ra of 3.0 pCi/l, there is relatively little information in the literature about radium removal or reduction in potable-water supplies. In 1974 and 1975 the Environmental Protection Agency funded two research projects in order to determine radium-removal efficiences in water treatment processes. One project was conducted by the Iowa Department of Environmental Quality[11], and the other by the Illinois Environmental Protection Agency[12]. These projects studied the removal efficiencies of lime-soda softening, ion-exchange, reverse osmosis and iron removal in an attempt to determine typical removal efficiencies for these processes. The removal efficiencies, radium-removal models, and waste stream radium concentrations assumed or calculated in this report were based largely on a compilation and analysis of data presented in the two aforementioned reports, along with supplemental data from the literature.

Data collected by state agencies on radium levels in Florida waters, as well as radium removal in several Florida water treatment plants, have also been included where applicable.

Assumed Radium Level in Finished Water

In order to arrive at specific treatment costs it was necessary to assume the level of radium which would remain in the finished water. This report assumes that level to be equal to proposed interim standard for ^{226}Ra plus ^{228}Ra of 5 pCi/l. It is recognized that many municipalities may set stricter standards for themselves and design their processes to reduce radium levels well below this limit. To do so will increase the costs of treatment above the costs reported in this report. In some cases, the operation of a plant will not be effective from a chemical water quality point of view unless a minimum removal of total hardness is effected by the process. This minimum total hardness removal may effect removal of radium to levels in the finished water below the proposed interim standard of 5.0 pCi/l. When radium is removed in the finished water below the limit of 5.0 pCi/l due to operationally required minimum hardness removals, the reported treatment costs are for the resulting lower radium level and not the 5.0 pCi/l level.

All radium removal data reported, analyzed and modeled in this report are based on measurements of the isotope ^{226}Ra. It is assumed in this report that the chemical behavior of ^{228}Ra will follow closely the observed behavior of ^{226}Ra in water treatment processes. Municipal water treatment plants (proposed or in operation) must determine the total radium level (^{226}Ra plus ^{228}Ra) and enter the design curves in this report for the total activity (pCi/l) observed. This procedure will ensure that the proposed interim standard will be satisfied.

Raw Water Quality Parameters

It was necessary to assume certain raw water quality parameters in order to calculate treatment costs. Table 2 contains the assumed values of three typical raw waters which represent the best compromise effectively spanning the range of water qualities found in the literature for waters in Iowa, Illinois, and Florida. The total dissolved solids range from a high of 2,000 mg/l to a low of 400 mg/l. The primary operational variable will be total hardness. Here the high, medium, and low levels will be 750, 300, and 150 mg/l as $CaCO_3$, respectively.

TABLE 2. RAW WATER QUALITY CONCENTRATIONS ASSUMED FOR CALCULATIONS

High Level Solids	mg/l as $CaCO_3$	mg/l as Ion
TDS		2000
TH	750	
Ca^{++}	500	200
Mg^{++}	250	60
ALK	300	360
Medium Level Solids		
TDS		1000
TH	300	
Ca^{++}	200	80
Mg^{++}	100	24
ALK	200	244
Low Level Solids		
TDS		400
TH	150	
Ca^{++}	100	40
Mg^{++}	50	12
ALK	100	122

TABLE 3. CORRELATION OF RAW WATER QUALITY PARAMETERS WITH RADIUM

	Ra^{226a}	TH^b	Ca^b	Mg^b	Fe^c	TDS^c	ALK^b	Ba^c	Bx^c
DCI, IL	3.26	286	153	133	0.44	1220	286	0.13	1.1
Peru, IL	5.82	298	188	110	0.44	890	318	0.13	0.63
Herscher, IL	14.3	404	226	178	0.12	1426	259	0.10	1.4
Elgin, IL	5.55	246	142	104	0.04	350	303	8.7	0.23
Lynwood, IL	14.7	849	620	229	0.60	1766	215	0.09	1.2
Greenfield, IA	14.0	630	400	230	1.6	2160	190	<0.10	----
Adair, IA	6.30	710	450	260	0.58	1905	158	<0.10	----
Stuart, IA	16.0	640	375	265	0.94	1770	182	<0.10	----
Eldon, IA	50.0	400	246	154	1.9	1228	252	<0.10	----
Estherville, IA	5.2	915	600	315	1.6	1350	367	<0.10	----
Grinnel, IA	6.2	368	205	163	1.1	784	298	<0.10	----
Holstein, IA	14.0	920	600	320	1.8	1510	288	<0.10	----
Webster City, IA	7.1	530	275	255	0.69	1010	294	<0.10	----
West Des Moines, IA	9.6	376	210	166	0.36	1200	260	<0.10	----
Sarasota, FL	4.30	460	---	---	----	----	----	----	----
Venice, FL	8.73	570	---	---	----	----	----	----	----
Englewood, FL	1.69	360	---	---	----	----	----	----	----
Mean	11.0	527	335	206	0.87	1327	262	1.80	0.91
r*	----	0.057	0.036	0.048	0.518	0.176	0.252	0.335	0.628
rα = 0.05**	----	0.606	0.532	0.532	0.532	0.532	0.532	0.878	0.878

*Correlation coefficient for bivariate linear regression of ^{226}Ra with associated chemical parameter

**Correlation coefficient for significance at α = 0.05 level

a pCi/1

b mg/1 $CaCO_3$

c mg/1

Raw Water Radium and Water Quality

The raw water data available have been analyzed with respect to a possible correlation between raw water quality parameters and raw water radium concentration. Table 3 contains a compilation of raw water data identified by location. A bivariate linear regression analysis of the data demonstrates that no significant correlation exists between raw water radium and any other raw water quality parameter tested at the 95 percent confidence level. A trend toward significance is noted for the presence of the heavy metals, iron, barium, and boron along with radium. This trend is not sufficiently useful to predict the concentration of raw water radium and thus it will be assumed that the radium concentration in raw waters is a random variable with respect to all other raw water quality parameters.

Required Removal Fraction for Radium

Since the limit in the finished water is set and the concentration in the raw water is a random variable with respect to water quality, the required removal fraction for radium is a direct function of the raw water radium content. This can be expressed by the following equation:

$$f = 1 - (5/RWR) \qquad \text{(Eq. 1)}$$

where f = radium removal fraction required and RWR = raw water radium concentration. Figure 1 is a graphical representation of this equation.

Population Ranges Studied

Treatment costs are reported according to the population served by the water system. Table 4 shows the population range investigated for each treatment process and the hydraulic flow range assuming a per capita water consumption of 150 gallons per capita per day (gpcd), or 0.568 cubic meters per capita per day.

TABLE 4. POPULATION AND FLOW RANGE INVESTIGATED

	Population Range	Flow Range Cubic Meters/Day
Lime-Soda Softening	2000 - 1,000,000	1140 - 568,000
Ion Exchange	100 - 50,000	56.8 - 28,400
Reverse Osmosis	100 - 50,000	56.8 - 28,400

COST DETERMINATION

General

Costs reported here have been developed from published data, information

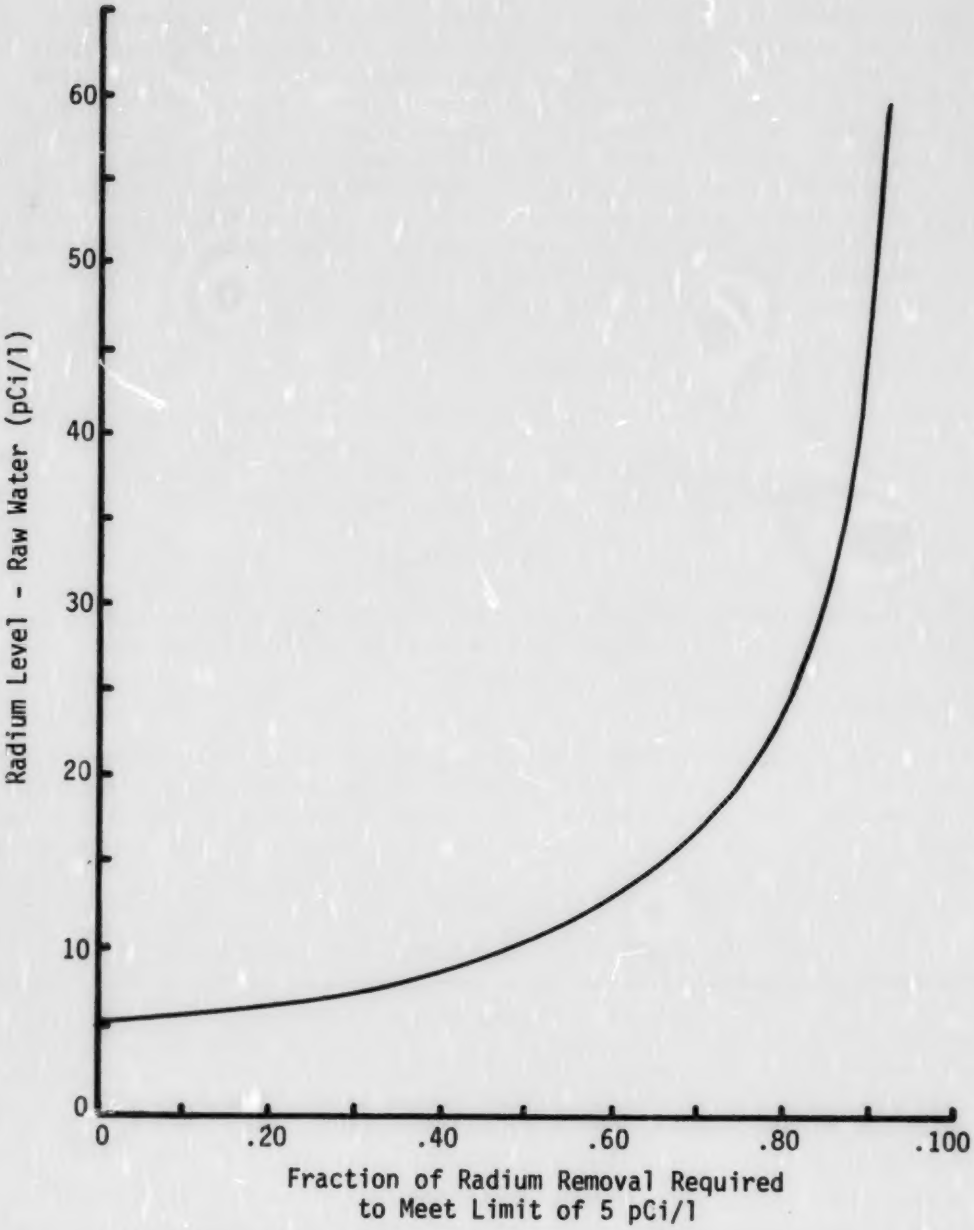


FIGURE 1. REQUIRED REMOVAL FRACTION FOR RADIUM

obtained from equipment manufacturers and suppliers, and data obtained from actual construction costs of existing plants.

The costs developed in this report are intended as a guide in the development of planning estimates only and not in the preparation of bid documents or detailed cost estimates. Exact capital and operating costs are highly variable from location to location within the United States, even for plants of the same size and design. Variables such as local costs of land, materials, and labor; state or regional differences in building codes; availability of and existing facilities suitable for modification may accentuate the differences in treatment costs for similar plants.

The cost data, along with sample calculations which appear in the appendix, are of sufficient flexibility to enable the planner to make adjustments to the reported costs, when local information is available. For example, operation and maintenance cost curves can be reduced if the locally delivered cost of chemicals is less than the assumed cost upon which the estimates are based. In addition, cost indices are used to provide a baseline for projecting costs, and for estimating escalation due to inflation. The indices used in this report are national indices, readily available to the user. These indices are often available for major U.S. cities or on a regional basis and these local or regional indices may be substituted, if desired.

Basis of Cost Estimates

(1) The cost indices used in this report are:

a. Engineering News-Record-Building Cost Index (ENR BCI). This index was introduced in 1938 in order to measure the effects of wage and materials price trends. The Building Cost Index has skilled labor and materials components and is used for cost estimates for buildings, site development, utilities, and general civil construction. The national average ENR BCI appears weekly in the "Scoreboard" section of Engineering News-Record Magazine. City-by-city Building Cost Indices for 22 U.S. cities appear monthly in the second ENR issue of the month. The ENR BCI used in the report for all appropriate curves unless otherwise noted is 1351 for October, 1975.

b. Bureau of Labor Statistics - Labor Costs Index. The index used in this report is for personnel in Standard Industrial Category (SIC) 494.7, or Water, Steam and Sanitary Systems Non-Supervisory workers. The base BLS Labor Cost Index for October 1975 is 5.02, the index has been modified to 7.28 to include overhead and payroll expense (30% overhead, 15% payroll expense). This information can be obtained from Employment and Earnings Statistics on the Labor Force, published monthly by the U.S. Department of Labor, Bureau of Labor Statistics.

c. U.S. Bureau of Labor Statistics - Chemical Index. The index used in this report to indicate chemical price trends is 209, which is the October, 1975 Industrial Chemicals (Index; Code 061). This information can be obtained from the Wholesale Prices and Price Indexes

Data, published monthly by the U.S. Department of Labor, Bureau of Labor Statistics.

(2) Chemical costs used in this report are reported in Table 5.

TABLE 5. CHEMICAL PRICES USED IN CALCULATIONS

Chemical	Price Per Ton	Source
Soda Ash (Na_2CO_3) 57% as Na_2O	$87.00	February 19, 1976 ENR
Lime (CaO) (Quicklime) 96%	48.00	Delivered at Gainesville, FL Average of two suppliers 2/76
Salt (NaCl) (Rock Salt) 99%	40.00	Delivered at Gainesville, FL Average of two suppliers

(3) Costs reported as capital Costs include:

a. Construction for Site Preparation including--
   Grubbing, Cleaning, Grading
   Roads
   Fences and Gates
   Utilities
   Service Buildings
   Design and Specifications
   Construction Supervision

b. Plant Construction including--
   Piping and Controls
   Civil Construction
   Mechanical Equipment
   Design and Specifications
   Construction Overhead

c. Land Costs - assumed to be $750/hectare ($1850/acre)

d. Interest During Construction at 8 percent per annum

e. Start Up Costs - 1/12 or 1/6 of annual operating costs, depending on plant size.

f. Owners General Expense - 12 percent of total construction costs (a + b), 9 percent for large plants.

g. Working Capital, 1/16 or 1/12 of annual operating costs, depending on plant size.

(4) Costs reported as Operating and Maintenance Costs Include:

   a. Chemical Costs

   b. Labor

   c. Operation and Maintenance Costs, such as utilities, annual replacement of expendable items, etc.

(5) Total annual costs are based on amortization at 8 percent compound interest for depreciating capital, 8 percent simple interest for non-depreciating costs, unless otherwise specified. The useful life of lime-soda plants was assumed to be 40 years, 20 years for ion exchange and reverse osmosis.

The major source and method of determining treatment plant costs were derived from "Monograph for Determining Costs of Removing Specific Contaminants from Water," prepared for the EPA by David Volkert and Assoc.[13] Sample calculations for each of the three treatment processes are shown in the appendix.

It should be noted that the cost curves for radium removal derived in this report are costs associated with construction and installation of entirely new treatment facilities. It has been assumed for the purposes of this report that the only existing water supply facilities are:

(1) Developed raw water source such as a deep well field, infiltration gallery, impounded surface supply, etc., and

(2) Water transmission and distribution system.

Many municipalities or water supply utilities in areas where radium levels exceed the interim standard have treatment facilities which, with process modifications, or construction of additional facilities, can be upgraded to deliver finished water meeting the radium standard at substantially less cost than that presented in this report.

The real cost of treatment facilities associated only with removal of radium to acceptable levels can span the continuum between the utility whose existing facilities already meet the radium standard to the utility which presently distributes chlorinated raw water and must construct entirely new treatment facilities.

An illustrative example of estimating costs associated with upgrading existing facilities for increased radium removal is shown in Appendix E.

SECTION VI

LIME-SODA SOFTENING

GENERAL

The hardness of almost all water supplies is caused by the presence in solution of calcium and magnesium ions. Other divalent ions such as strontium, ferrous iron and manganese may contribute to the hardness to a much lesser degree.[14] The lime-soda process is a precipitative softening process which uses the addition of lime (CaO-quicklime, or $Ca(OH)_2$-slaked or hydrated lime) to convert the soluble bicarbonates of calcium and magnesium into insoluble calcium carbonate and magnesium hydroxide. This is the removal of "carbonate hardness", or the calcium and magnesium ions associated in solution with the bicarbonate ion. Calcium and magnesium associated with the sulfate, chloride or other ions, ("non-carbonate hardness"), are removed by the addition of both lime and soda ash (Na_2CO_3) which provides the carbonate ion necessary for formation of calcium carbonate. Since magnesium removal occurs only above a pH of about 11 at normal water temperatures, excess lime sufficient to raise the pH to ≈11 must be added prior to removal of magnesium as magnesium hydroxide.

The precipitated compounds are flocculated, settled, and removed as sludge while the clarified effluent is usually filtered in order to polish the effluent by removing residual floc particles.

The chemistry of water softening is probably best explained or illustrated by showing the chemical reactions that take place when lime and soda ash are added to water containing calcium and magnesium salts. The reactions in the lime-soda process, then are:[14]

$$CO_2 + Ca(OH)_2 = CaCO_3\downarrow + H_2O \tag{1}$$

$$Ca(HCO_3)_2 + Ca(OH)_2 = 2CaCO_3\downarrow + 2H_2O \tag{2}$$

$$Mg(HCO_3)_2 + Ca(OH)_2 = CaCO_3\downarrow + MgCO_3 + 2H_2O \tag{3}$$

$$MgCO_3 + Ca(OH)_2 = CaCO_3\downarrow + Mg(OH)_2\downarrow \tag{4}$$

$$2NaHCO_3 + Ca(OH)_2 = CaCO_3\downarrow + Na_2CO_3 + 2H_2O \tag{5}$$

$$MgSO_4 + Ca(OH)_2 = Mg(OH)_2\downarrow + CaSO_4 \tag{6}$$

$$CaSO_4 + Na_2CO_3 = CaCO_3\downarrow + Na_2SO_4 \tag{7}$$

These equations show all of the reactions taking place in softening a water containing both carbonate and noncarbonate hardness by the lime-soda process. It should be noted that, in Equation 1, the carbon dioxide is not hardness as such, but in proportion to its content in the water will consume lime and must therefore be considered in calculating the amount of lime required. Similarly, in Equation 5, the sodium bicarbonate or sodium alkalinity, if present, is not part of the hardness but, since it is included in the total alkalinity, it will consume lime. Equations 2 and 4 show the removal of carbonate hardness by lime. Whereas only one molecule of lime is required for one molecule of calcium bicarbonate, Equation 2, two molecules of lime are required for the removal of one molecule of magnesium bicarbonate, Equations 3 and 4. Equation 6 shows the removal of magnesium noncarbonate hardness, shown as magnesium sulfate, by lime. No softening is effected by this reaction because, for each molecule of magnesium noncarbonate hardness removed, an equivalent amount of calcium noncarbonate hardness is formed. Equation 7 shows the removal of calcium noncarbonate hardness, shown as calcium sulfate, either originally in the water or formed as shown in Equation 6.

From these reactions it is apparent that the amounts of lime and soda ash required to soften a water may be calculated from the concentrations of free carbon dioxide, bicarbonate (usually the total alkalinity), magnesium hardness, and noncarbonate hardness.[15]

Figure 2 shows a diagram of the two typical types of lime-soda softening plants. In the horizontal flow plant of Figure 2a, chemical mixing, flocculation, and sedimentation are usually carried out in separate basins as separate unit operations. Upflow or solids contact units, shown in Figure 2b, combine the three above-mentioned processes in one physical unit. Upflow clarification is less expensive due to the obvious reduction in the number of process units and smaller area required for plant layout; however, horizontal flow units provide more positive control of the overall process and are better able to absorb peaks in plant loading by allowing greater detention time in the plant.

RADIUM REMOVAL IN THE LIME-SODA PROCESS

Soluble radium, a divalent alkaline earth metal ion similar to calcium and magnesium is also removed in the lime-soda softening process. Table 6 shows the radium and total removal hardness efficiencies of six lime-soda softening plants in the United States. The data from Iowa and Illinois are the most reliable, in that radium and hardness analyses were performed on water samples taken at the same time. The hardness data from Florida, on the other hand, were reconstructed from plant operating records on the same day that the radium samples were taken by another agency. This means that the two samples may have been taken as much as eight hours apart. It can be seen from Table 6 that radium removal varied from plant to plant and ranged from 59-96 percent removal, averaging 80 percent. Figure 3 shows a plot of total hardness removal versus radium removal based on the data presented in Table 6. If the two points from Florida plants are discounted, the line $y = x^{2.86}$ fits the data reasonably well and serves as the basis for a radium removal model in lime-soda plants.

FIGURE 2a. HORIZONTAL FLOW PLANT

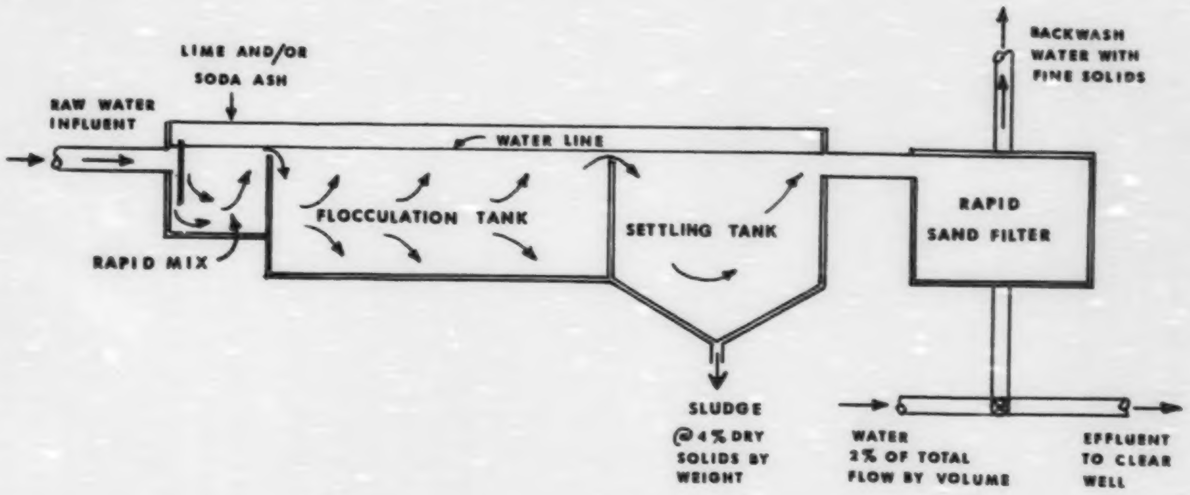
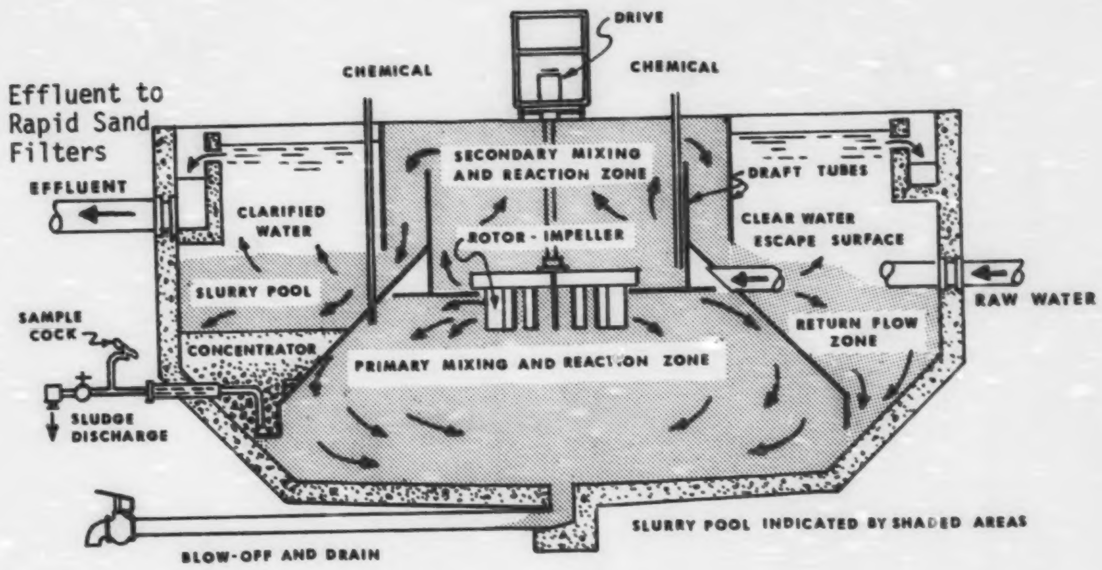


FIGURE 2. DIAGRAM OF TYPICAL LIME-SODA TREATMENT PLANT

FIGURE 2b. SOLIDS CONTACT OR UPFLOW PLANT



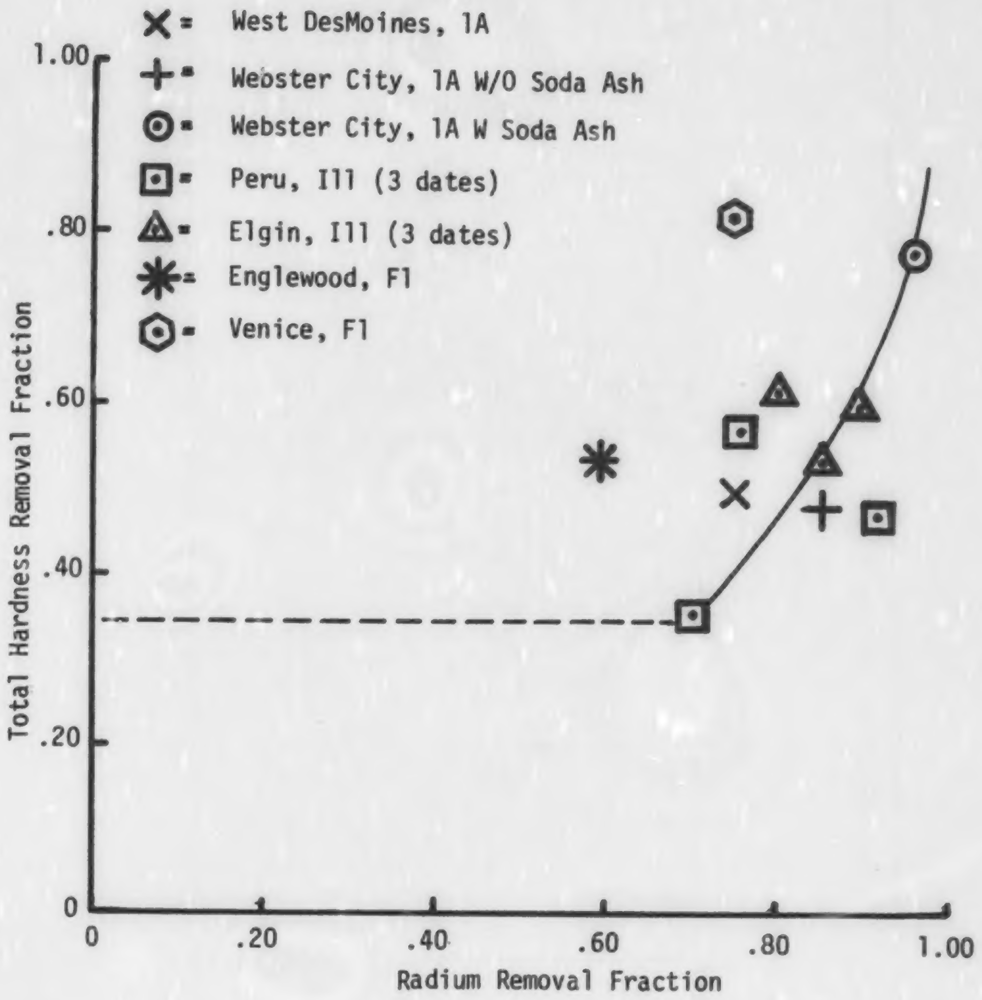


FIGURE 3. LIME SODA PROCESS, TOTAL HARDNESS REMOVAL FRACTION VS RADIUM REMOVAL FRACTION.

TABLE 6. RADIUM^{226} AND TOTAL HARDNESS REMOVAL EFFICIENCIES LIME-SODA SOFTENING

LOCATION	CLARIFIERS							FILTERS						OVERALL	
	Ra in pCi/1	Ra out pCi/1	% RA Removal	TH In mg/1 $CaCO_3$	TH Out mg/1 $CaCO_3$	% TH REM	pH Treatment	RA In pCi/1	RA Out pCi/1	% Ra Removal	TH In mg/1$CaCO_3$	TH Out mg/1 $CaCO_3$	% TH REM	% Ra REM	% TH REM
W. Des Moines, IA 8/1/74	9.3	2.6	72	376	215	43	10.4	2.6	2.35	10	215	190	12	75	49
Webster City, IA. Clarifier #1 8/13/74	6.1	1.9	69	507	333	34	10.05	1.9	0.9	53	333	262	21	85	48
Webster City, IA Clarifier #2 8/13/74	6.1	2.6	57	507	282	44	10.1	2.6	0.9	65	282	262	7	85	48
Webster City, IA Clarifier #1 2/20/75	7.8	0.9	88	482	150	69	10.95	0.9	0.3	67	150	106	29	96	78
Webster City, IA Clarifier #1 2/20/75	7.8	0.3	96	482	150	69	10.95	0.3	0.3	0	150	106	29	96	78
Peru, IL 2/20/75	6.49			329			8.4		0.51			174		92	47
Peru, IL 2/25/75	5.49			278			8.4		1.62			180		70	35
Peru, IL 3/4/75	5.48			286			8.4		1.33			122		76	57
Mean	5.82			289					1.15			147		79	49
Elgin, IL 3/7/75	7.45			246			10.2		.75			99		90	60
Elgin, IL 3/14/75	5.7			243			10.2		.80			112		86	54
Elgin, IL 3/21/75	3.51			242			10.2		.71			95		80	61
Mean	5.55			244					.75			102		85	59
Venice, FL 8/7/75	8.73			570			9.7		2.19			100		75	82
Englewood, FL 8/7/75	1.69			360			8.5		.69			166		59	54

The data experience considerable scatter; however, a reasonable model for the lime-soda process is given in Equation 2:

$$\text{Total Hardness Removal Fraction} = (f)^{2.86} \qquad \text{(Eq. 2)}$$

It is obvious that many plants will not operate at total hardness removals much below 45 percent. A lower limit of 35 percent total hardness removal has been chosen. This limitation places a lower limit upon the radium removal fraction of 69 percent.

REQUIRED TOTAL HARDNESS REMOVAL

The project will consider raw water radium concentrations from 7.5 to 50 pCi/l. By substitution of Equation 1 into Equation 2, the total hardness removal can be expressed as a function of the raw water radium concentration.

$$\text{Total Hardness Removal Fraction} = [1 - (5/RWR]^{2.86} \qquad \text{(Eq. 3)}$$

This function is graphically presented in Figure 4.

Because of the 35 percent lower limit on total hardness removal all the waters containing 16 pCi/l or less of radium will receive a 69 percent radium removal. Figure 5 shows the finished water radium concentrations for the lime-soda process as a function of raw water radium concentration.

Figure 6 is a plot of radium removal efficiency versus pH from plant data. This plot was made in order to determine if radium removal was dependent on pH of treatment. This figure shows a clear trend toward higher radium removal efficiencies as increased pH. The number of data points is insufficient to establish the statistical significance of this relationship and so it is presented here for illustrative purposes. It is, of course, generally true that total hardness removal increases with pH in the lime-soda process. The adjustment of the pH over and above that normally used in hardness removal is not considered to be a viable operational parameter to effect increased radium removal.

WASTE STREAMS

There are two effluents to be considered: lime sludge and backwash waters. The lime sludge is a combination of the chemicals used, hardness removed, and other contaminants, such as radium, that will settle within the time frame of the clarifier design. The clarified overflow then goes to a sand filter to remove those particles and materials that were not removed in the sedimentation unit. Periodically the sand filter must be backwashed to clean and remove these carry-over particles.

The sludge solids are principally $CaCO_3$ and $Mg(OH)_2$ with varying amounts of other cations, clay, sand, and other trace metal contaminants such as

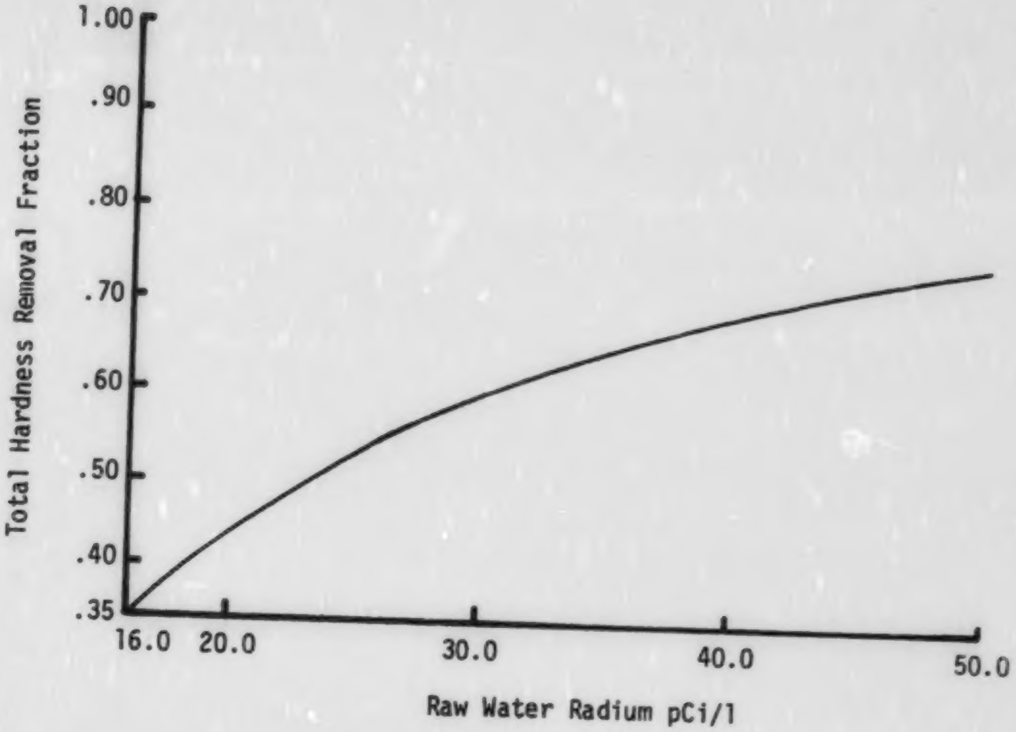


FIGURE 4. TOTAL HARDNESS REMOVAL FRACTION AS A FUNCTION OF RAW WATER RADIUM CONTENT REQUIRED TO MEET LIMIT OF 5.0 pCi/l FINISHED WATER.

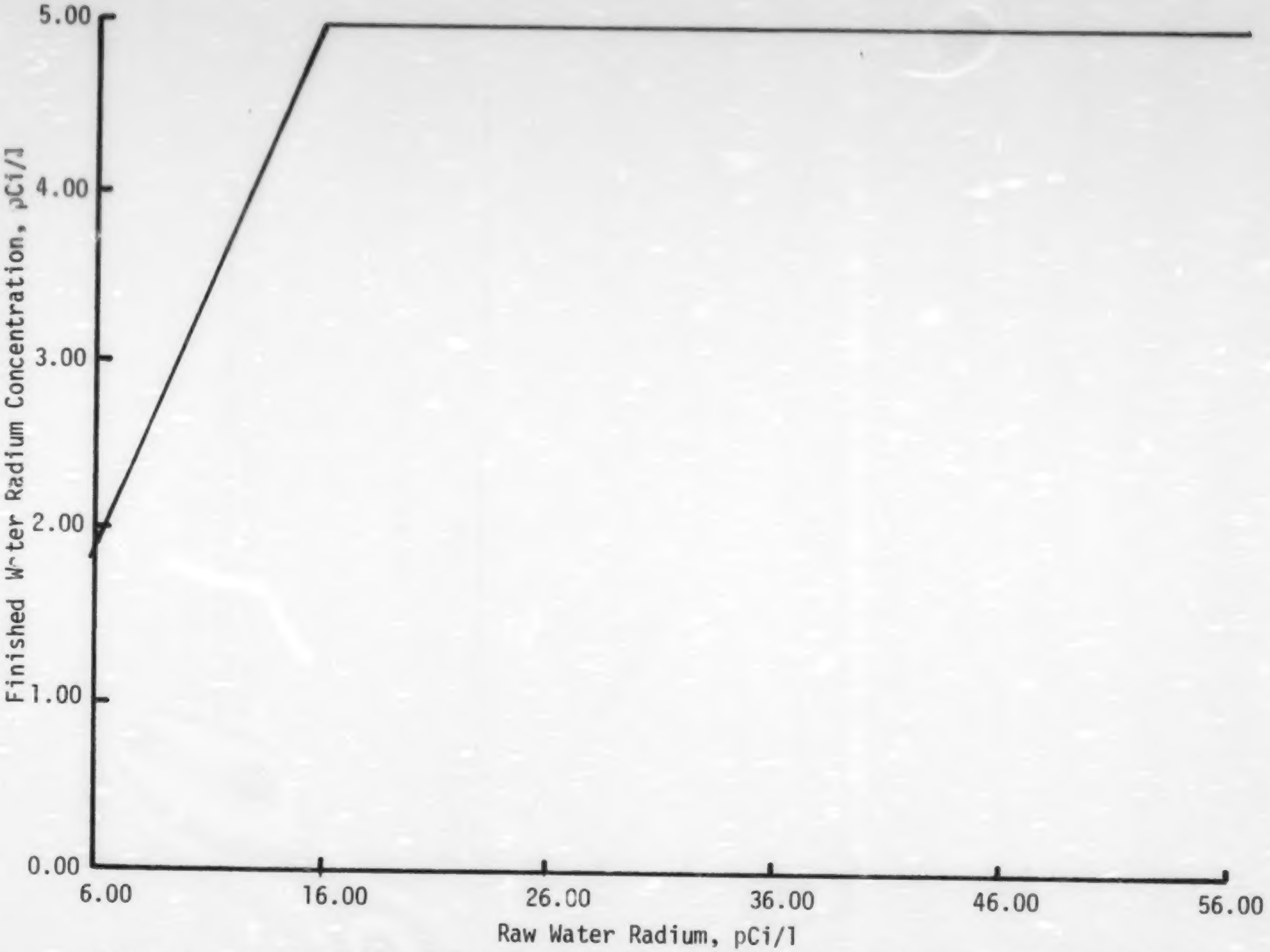


FIGURE 5. FINISHED WATER RADIUM CONCENTRATION VERSUS RAW WATER RADIUM CONCENTRATION FOR LIME-SODA SOFTENING

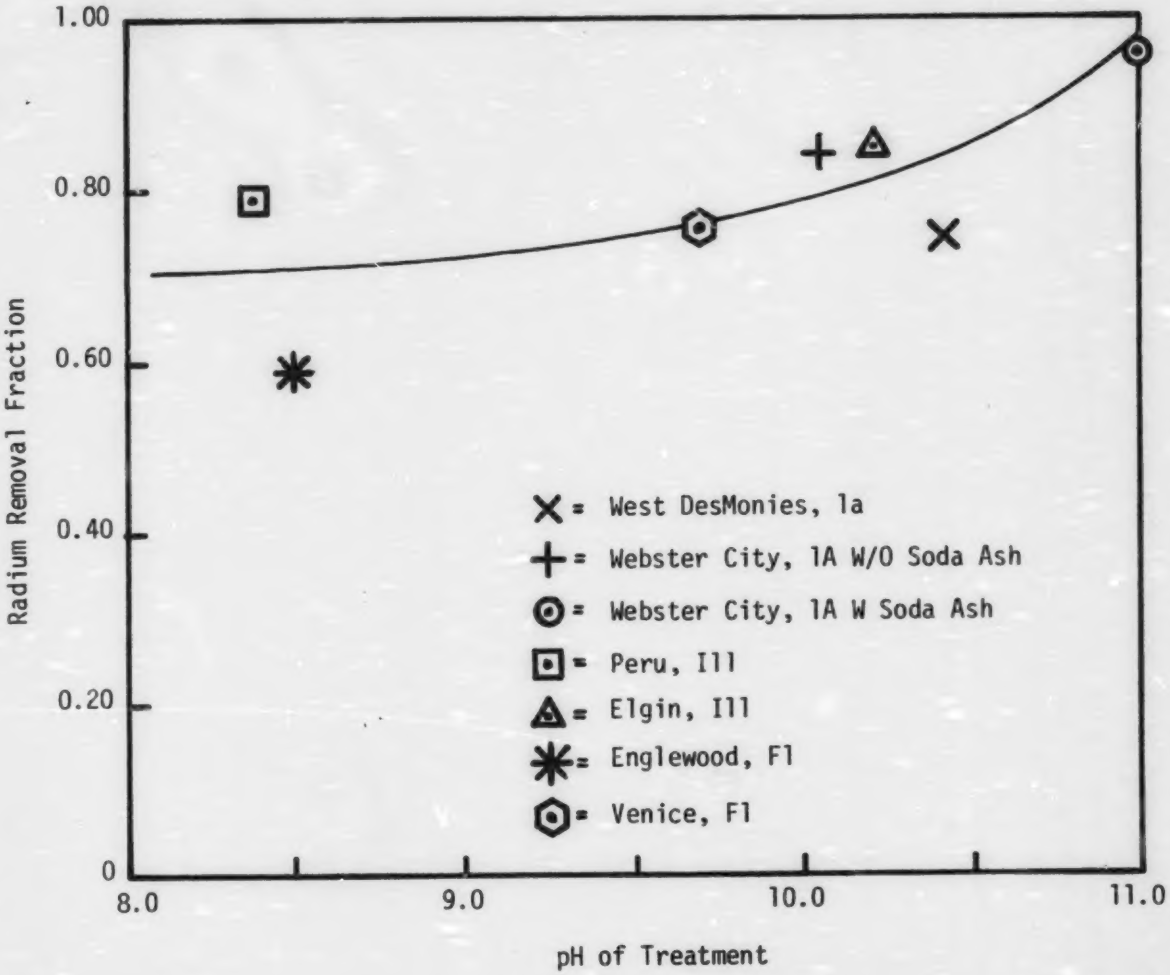


FIGURE 6. RADIUM REMOVAL FRACTION VS pH OF TREATMENT, LIME SODA PROCESS.

radium. The exact characteristics depend upon the raw water quality. In this report the settled sludge will be assumed to be 4 percent solids. The amount of sludge produced per day is a direct function of the total hardness removed and the plant capacity. Radium concentration in the sludge will depend upon the total hardness removed as well as the raw water radium concentration. The best available data[11] indicate that about 97 percent of the radium removed by the plant will appear in the lime sludge.

Backwash water is normally settled and the supernatant recirculated to the head of the plant and its quality will be degraded by the fine particles accumulated on the filter since the previous washing. These fine particles will normally be on the order of 3 percent of the lime sludge production. The best available data[11] indicate that about 2 percent of the finished water flow is used for backwash purposes:

$$\text{Backwash flow, gal/day} = (0.02)\ (150)\ (\text{Pop.}) = 3\ (\text{Pop.}) \qquad \text{(Eq. 4)}$$

Normally a holding tank is provided to achieve some sedimentation prior to discharge. Radium concentration in the backwash is considered to be about 3 percent of the radium removed by the plant. Newer plants have recirculated the holding tank effluent to the head end of the plant whereas older plants primarily discharge the backwash to a sanitary sewer.

Lime Sludge Production

The production of lime sludge in terms of dry sludge per million gallons of plant capacity is primarily a function of the total dissolved solids and the total hardness removal fraction.

Table 7 shows the pounds of dry sludge per million gallons produced at the various input conditions. The sludge production is based upon a factor of 3.5 pounds of dry sludge produced per pound of hardness removed as calcium carbonate. The theoretical sludge production would be 2.0 pounds of dry sludge produced per pound of hardness removed. The difference is due to water of hydration in the calcium carbonate and magnesium hydroxide sludge matrix which cannot be removed by dewatering or heating to 105°C. The factor 3.5 pounds of dry sludge per pound of hardness removed is based upon extensive experimental work by Burgess and Niple, Ltd. on lime-soda softening sludges in the state of Ohio[16]. The sludge production versus total hardness removal is graphed in Figure 7. Analysis of the curve indicates the expressions:

$$\text{Dry Sludge Production} = 21{,}900\ (\text{Total Hardness Removal at 2000 mg/1 TDS}) \qquad \text{(Eq. 5)}$$

or

$$\text{Dry Sludge Production} = 8760\ (\text{Total Hardness Removal Fraction at 1000 mg/1 TDS}) \qquad \text{(Eq. 6)}$$

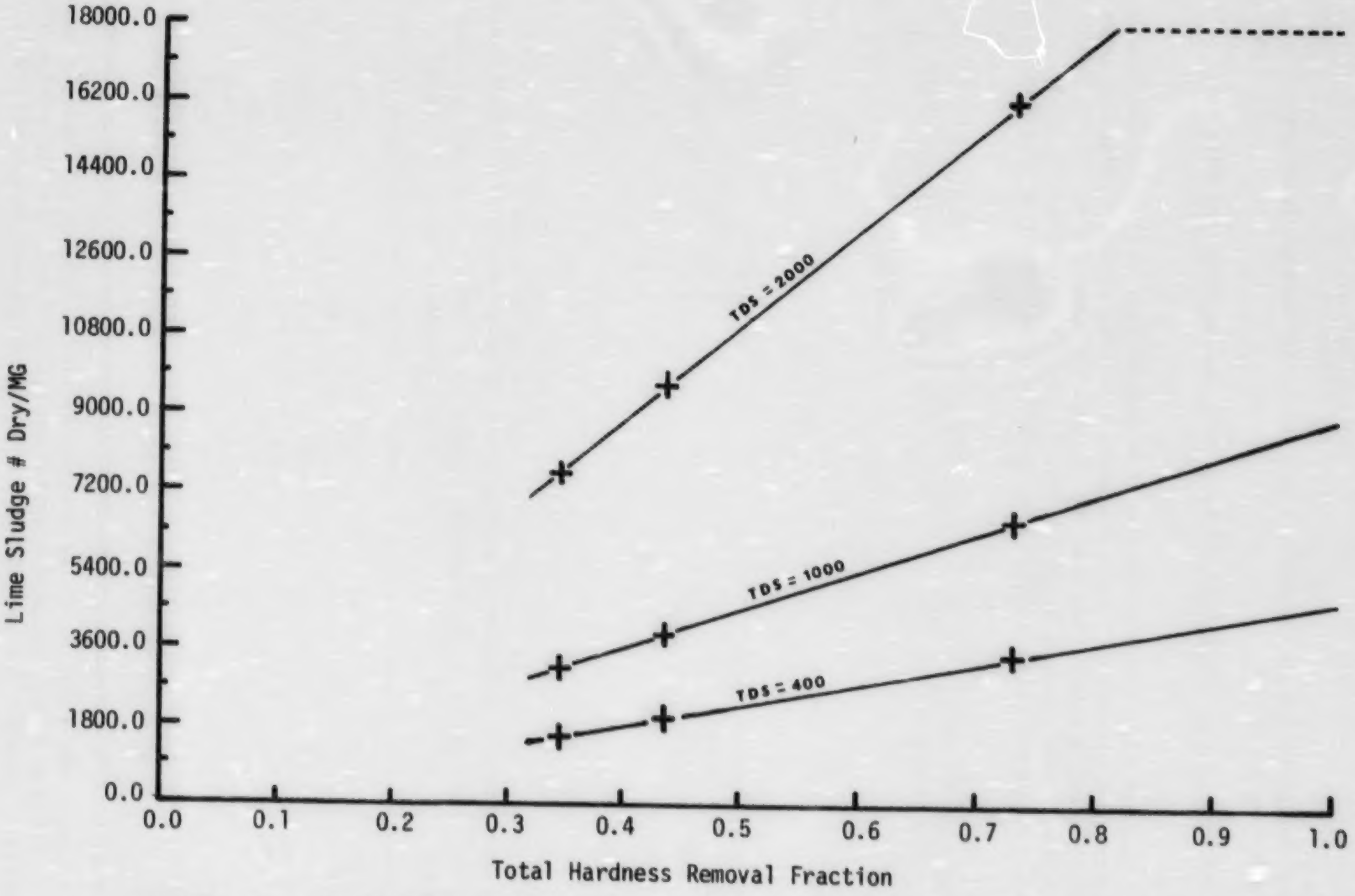


FIGURE 7. LIME SLUDGE PRODUCTION VERSUS HARDNESS REMOVAL FOR VARIOUS TOTAL DISSOLVED SOLIDS

or

$$\text{Dry Sludge Production} = 4400\ \text{(Total Hardness Removal Fraction at 400 mg/l TDS)} \qquad \text{(Eq. 7)}$$

where the dry sludge production is in pounds per million gallons.

This report will assume that the lime sludge will exit these sedimentation units at 4 percent solids. Therefore, the wet sludge production rate will be 25 times greater than the dry production rate (DSP). Since 9 percent of the radium removed by the plant will be contained in the lime sludge, it is possible to predict the radium concentration as follows:

$$\left[\begin{array}{l}\text{Radium Concentration,}\\ \text{Wet Lime Sludge,}\\ \text{Picocuries/Kg}\end{array}\right] = 1.42 \times 10^{5} \left[\begin{array}{l}\text{RWR - 5}\\ \text{Dry Sludge}\\ \text{Production, lb/MG}\end{array}\right] \qquad \text{(Eq. 8)}$$

For RWR >16 pCi/l and

$$\left[\begin{array}{l}\text{Radium Concentration,}\\ \text{Wet Lime Sludge}\\ \text{Picocuries/Kg}\end{array}\right] = 1.01 \times 10^{5} \left[\begin{array}{l}\text{RWR}\\ \text{Dry Sludge}\\ \text{Production, lb/MG}\end{array}\right] \qquad \text{(Eq. 9)}$$

For RWR <16 pCi/l.

TABLE 7. LIME-SODA SLUDGE CALCULATIONS

Solids TDS, Mg/l	RWR pCi/l	Ra Removal %	THR %	Amt. TH Mg/l as $CaCO_3$	Dry wt. sludge lb/MG
2000	7.5	69	35	262	7648
2000	20	75	44	330	9633
2000	50	90	74	555	16200
1000	7.5	69	35	105	3065
1000	20	75	44	132	3853
1000	50	90	75	222	6480
400	7.5	69	35	52	1518
400	20	75	44	66	1927
400	50	90	75	111	3240

However, the total hardness removal is not allowed to fall under 35 percent even at low raw water radium concentration. Therefore, the dry sludge production is a constant for each of the three water qualities for all RWR's less than 16 pCi/l. Typical values for radium concentration are shown in Table 8 as calculated for the plants with the indicated size at various RWR and TDS values. As one would expect, the concentration of removed radium increases as the TDS decreases, but remains constant with changes in population for a given raw water radium concentration. The highest radium concentration in the table is associated with 50 pCi/l RWR and a low TDS of 400 mg/l. The value here is about 4,500 pCi/kg wet weight. If this sludge is dewatered to a "dry" state of about 70 percent solids, the concentration would increase to about 78,880 pCi/kg. Normal surface soils may average some 700 pCi/kg. Disposal methods must therefore look to either containment or dilution with soil or other material such as municipal solid waste, at a volume ratio of approximately 100 to 1. At the lower raw water radium concentration of about 16 pCi/l and high TDS (2000 mg/l) the radium concentration in the sludge drops by an order of magnitude. The "soil" dilution necessary to reduce the concentration to "background" levels is then lowered to a 10 to 1 ratio.

TABLE 8. TYPICAL VALUES OF LIME SLUDGE PRODUCTION AND RADIUM CONCENTRATION

Parameters				
RWR pCi/l	TDS mg/l	Pop. millions	Prod. of Wet Sludge lb/day	Concentration pCi/kg wet
50	2000	1.0	6.08×10^7	8.96×10^2
16	2000	1.0	2.87×10^7	4.65×10^2
50	2000	0.02	1.22×10^6	8.96×10^2
16	2000	0.02	5.74×10^5	4.65×10^2
50	1000	1.0	2.43×10^7	2.24×10^3
16	1000	1.0	1.15×10^7	1.16×10^2
50	1000	0.02	4.86×10^5	2.24×10^3
16	1000	0.02	2.30×10^5	1.16×10^3
50	400	1.0	1.22×10^7	4.48×10^3
16	400	1.0	5.69×10^6	2.35×10^3
50	400	0.02	2.43×10^5	4.48×10^3
16	400	0.02	1.14×10^5	2.35×10^3

Backwash Production

The settling tank effluent in a horizontal flow tank or the unit effluent in a solids contact or upflow plant is routed to a rapid sand filter. These filters remove fine particles that did not settle in the previous unit. Filters are normally backwashed once each 24 hours to remove the accumulated material. Generally, about 2 percent of the total water softened is used for this purpose. Under normal conditions, backwash water is extremely dilute, but the solids concentration can be appreciable at times when processes preceding filtration are not functioning properly[11].

Under normal conditions when radium contamination is not a problem, backwash water should be held briefly for rough settling and recirculated to the head end of the plant.

The quality of backwash water is generally good if solids are allowed to settle out. Therefore, if holding facilities are installed, it is practical to recirculate this effluent through the waterworks rather than discharge it. Several statements indicate a potential problem with this procedure when radium is a contaminant: "Settling efficiency in the waterworks can also be expected to improve due to recirculation of calcium carbonate particles" and "should there be a build-up of fines in the mixed untreated water." The obvious conclusion is that there is a potential for recirculation of radium also. Radium would be expected to be in an insoluble form and accompany the fate of the solids. The only facilities required for recirculation are a waste holding tank and pumps. Initial investment is low and maintenance and operating costs are minimal.[11]

If the raw water radium is greater than 16 pCi/l, the amount of radium removed per day will be equal to 5 less than the effluent concentration multiplied by the flow in liters per day. The amount of radium that will show up in the backwash will be approximately 3 percent of that value. The best available data on the amount of water used in backwashing the filter indicates that about 2 percent of the flow is used. If these factors are combined, the flow parameters cancel out and the expression follows:

$$\text{Backwash Radium Concentration, pCi/l} = 1.5\ (\text{RWR}-5) \qquad \text{(Eq. 10)}$$

If the raw water radium is below 16 pCi/l, the expression changes to that shown in Equation 11:

$$\text{Backwash Radium Concentration, pCi/l} = 1.035\ \text{RWR} \qquad \text{(Eq. 11)}$$

These two expressions are shown graphically in Figure 8.

METHODS FOR LIME SLUDGE DISPOSAL

Alternatives for disposal of lime sludges are quite numerous and varied. The feasibility of many alternatives depends upon the population (plant capacity). Others may be limited by capital cost considerations. The approach in this report will be to consider the alternative, its practicality, and cost, initially without regard to the radium concentration. Then at various critical steps and at the end point, the radiological implications will be considered. Changes in limitations, precautions, or complete abandonment of the alternatives can then be addressed.

Several of the more important disposal alternatives are listed below.

I. Discharge
    A. Discharge to sanitary sewers

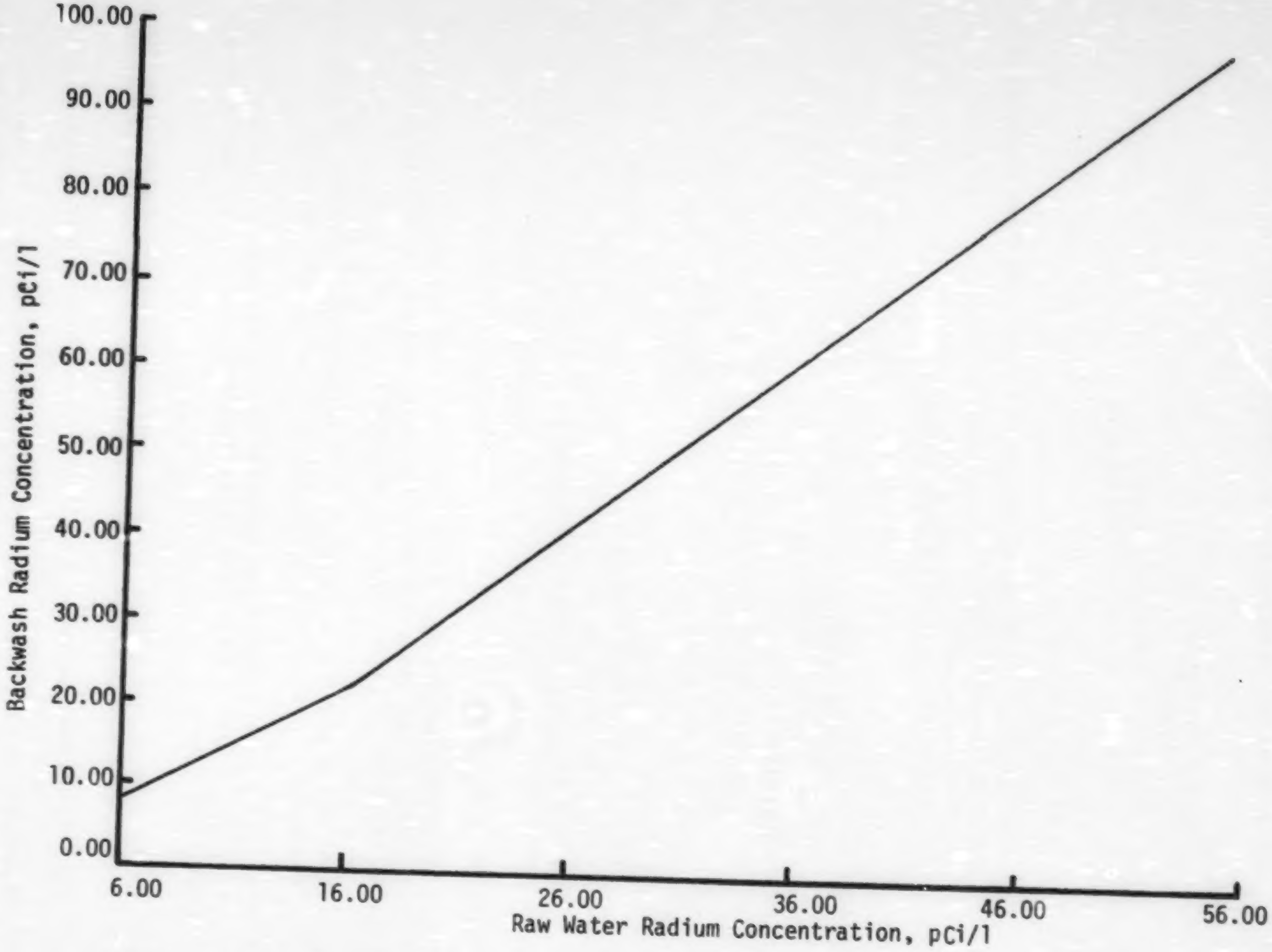


FIGURE 8. BACKWASH RADIUM CONCENTRATION, WITH LIME-SODA SOFTENING

- B. Discharge to local receiving water
- C. Wet pumping or trucking to local sanitary landfill

II. Storage
- A. Permanent lagooning
- B. Sanitary landfill
  - 1) With prior temporary lagooning
  - 2) With prior mechanical dewatering
    - a) Vacuum filtration
    - b) Centrifugation
    - c) Others
- C. Other natural or man-made depressions (all with some dewatering prior to transportation)
  - 1) Strip mine areas
  - 2) Borrow pits and quarries
  - 3) Others

III. Utilization
- A. Direct without drying
  - 1) Farmland and pasturelands
- B. With Prior Dewatering
  - 1) Farmland and pastureland
  - 2) Road Stabilization
  - 3) Calcination and recycle

IV. Disposal
- A. Direct - recharge to aquifers
- B. With prior dewatering
  - 1) Salt mines, coal mines, etc.
- C. As a nuclear waste

Discharge to Sewers

A report by Burgess and Niple[16] has an excellent discussion of discharge of lime sludge to sanitary sewers. Important points to be considered from a physical-chemical point of view are as follows:

(1) Pilot plant studies are needed to determine the tolerance of wastewater treatment processes to lime sludge at a particular facility.

(2) Primary settling tanks are required at the wastewater treatment plant to prevent lime sludge from being discharged to the secondary treatment processes.

(3) Holding tanks are needed so that lime sludge is discharged from the water treatment plant at a uniform rate.

(4) Provisions must be made for flushing and cleaning wet wells.

(5) Digester capacity must be provided for the additional sludge and digestor design must include additional mixing and provision for withdrawing more dense sludge.

(6) Lime sludge should not be discharged to installations having Imhoff tanks or similar units.

Since the sewer flow is on the order of 100 gpcd, the radium concentration in the sewer when the lime sludge is discharged to a sanitary sewer, will be nearly equal to the original raw water concentration. However, it is expected that the form of the radium will now be insoluble and wastewater treatment plants should remove over 95 percent of this insoluble radium. These factors lead to two basic conclusions: (1) the effluent of the wastewater treatment plant will have a radium concentration near that of the finished product of the water treatment plant regardless of the raw water radium concentration, and (2) the digested sludge will have a radium concentration on the same order of magnitude as the original lime sludge since the dry weight production of domestic sewage sludge is probably no greater than 1000 to 2000 lb/MG. Compare these values to the lime sludge production in Table 8.

The fate of the digested sewage sludge would therefore have to be controlled to the same degree as the original lime sludge. One should conclude, therefore, that discharge of lime sludge from a high radium water treatment facility to a sanitary sewer is not an attractive solution.

Discharge to Watercourse

Discharge of water treatment plant lime sludges into a watercourse has historically been a widespread practice in the industry. Recent Federal and State regulations now prohibit the discharge of waste sludges into streams. With the additional hazard of elevated radium concentrations, this practice should be discouraged.

Discharge to Sanitary Landfill

Lime sludge mixed with refuse reportedly aids in compaction of refuse in a landfill[16]. Some leachant will be produced if the sludge is not first dewatered to at least 20 percent solids. The behavior of radium under these conditions is not understood. It may remain insoluble and remain fixed within the sludge matrix during the early periods of leaching. On the other hand, its solubility may increase as the pH of the landfill decreases with age. Burgess and Niple[16] suggests that unless the lime sludges are dewatered, a town could not absorb, without leaching, more than 16 percent of its lime sludge in the size landfill the town would generate if the sludge were 4 percent solids.

Permanent Lagoons

A permanent lagoon can be designed for long term storage of lime sludges. Lagoons of about five to ten feet of depth and about 2.0 acres per million gallons per day per 100 milligram per liter of hardness removed are required[16]. The area is divided into at least six sections. Wet sludge is added in layers no more than 2 inches thick. This allows drying to about 70 percent solids, before the next layer is applied. Permanent lagoons may be reclaimed as useful land after the lagoon is filled. It may be paved or given an earth cover depending upon the expected use. Parking lots, playgrounds, golf courses, industrial parks, and recreational parks are more suggested uses.

Because of the radon daughter hazard potential, home building on reclaimed lagoons should be discouraged. Concentrations in the compacted sludge may approach 10^5 pCi/kg. Working Level (WL) is a measure of the alpha emitting radon daughters in an atmosphere. Starting with a "soil" concentration of 10^5 pCi/kg ^{226}Ra, one can estimate a working level of 0.2 in homes if they were built over this land.

This would also result in 340 μR/hr or about 3R/year outside over the land, a value much higher than the average occupationally exposed worker receives. Concentrations on the order of 10^4 pCi/kg can be expected to occur frequently; this is equivalent to about 0.02 WL or 0.3R/year, a magnitude triple the average national radiation background for the United States. With sludge particle size on the order of 3 to 8 microns, the smaller particles present a definite potential health hazard to the lung from both radium and its daughters. Because these particles adhere to each other as drying proceeds and also because of compaction, the air concentration potential should be reduced. However, the information necessary to assess this potential is not known.

If sludges are covered with overburden, shielding from gamma radiation results in addition to a concomitant reduction in potential airborne particulates of radium or its daughters.

Permanent lagoon design concepts could be used as foundations for sanitary landfills. This would (1) provide a water barrier and retard leachate transport, (2) neutralize acid effects, and (3) utilize less land. This is expecially important for Florida with its high water table and sandy soil.

Temporary Lagoons

Temporary lagoons may be used for thickening and dewatering a sludge before transport to another treatment method. Lagoons of 0.7 acres per million gallons per day per 100 milligrams per liter hardness removed are required, based on a depth of five feet[16]. Alternate filling of one of three sections to about one foot is suggested. With decanting and drying the section should achieve about 25 to 40 percent solids before the next application. Concentrations of ^{226}Ra will be on the order of 10^3 to 10^4 pCi/kg. "Dust" problems should be much less severe than the drier permanent lagoons. After sufficient build-up and dewatering, the sludge must be transported to another treatment site; however, the weight has now been significantly reduced.

When the percent solids in the sludge exceeds 20. it can be mixed with the refuse in a sanitary landfill without expecting leachant[16]. Dump trucks or power spreaders disperse the dewatered sludge during the fill or on top of the fill just prior to the dressing of the topsoil.

Mechanical Dewatering

Mechanical dewatering can reduce volume and increase solids content. Vacuum filtration and centrifugation are well known mechanical dewatering processes. Solids may exceed the 20 percent value with ordinary equipment and cycle times. Then the sludge would be suitable for mixing with refuse in a sanitary landfill. ^{226}Ra values would parallel those of the product from temporary lagoons. The primary disadvantage of the mechanical dewatering processes is its high capital and high operating costs, especially for small plants.

Application to Man-made Depressions

Burgess and Niple[16] have presented an excellent discussion of the application of lime sludge to strip mine areas. Here the sludge would aid in the reclamation of the soils and reduce the problem of acid mine drainage. The acidity, however, may eventually convert the stored radium to a more soluble form. Large quantities of sludge could be handled in the mined area, but the distances involved may make transportation costs excessively high. The costs would have to be weighed against the benefit from the reclaimed lands or reduction of the problem acid mine drainage. The fate of possible radium leachates will depend upon the characteristics of the deposits and the hydrology of the area. Use of reclaimed land would depend greatly upon the final concentration in the soil cover and the potential for radium uptake in the cover vegetation or the potential hazard of uptake if it were to exist. For example, forestry would be more favorable than cropland or pasture. The difference between the latter two choices may not be evident without further investigation.

Other man-made depressions should be considered. Abandoned quarries, for example, limestone or aggregate, may provide excellent storage. Dewatered lime sludges along with other material may provide reclamation of these areas. Another type of storage would be borrow pits, although volume and accessibility may be limiting factors.

Application to Farmland

Application of "waste" lime sludges to farmland is a sensitive issue to some farmers. Application of the same sludges containing measurable quantities of "radioactive" materials will be an even more sensitive issue. Burgess and Niple[16] present a thorough discussion of the need, value and disadvantages of the concept of liming farmlands, however, there is no consideration of the case where the sludge may come from high radium raw waters. Without regard to radium, the major advantages and disadvantages are listed below.

Advantages--

(1) Liming of vast area of farmland would be desirable.
(2) Lime sludge has more neutralizing power than marketed lime.
(3) Lime sludge has an excellent size distribution
(4) Lime sludge provides calcium and magnesium, both essential for plant growth.

(5) Liming increases the availability of phosphorus, molybdenum, and magnesium.
(6) Liming reduces harmful concentrations of aluminum, manganese, and iron.
(7) Liming increases favorable microbial activity in many soils.
(8) Liming results in better soil structure.

Disadvantages --

(1) Farmer acceptability of the concept is low.
(2) Transportation costs limit radius.
(3) Application methodology needs investigation.
(4) Competition with commercial lime producers.
(5) Application times are limited to certain seasons and to dry soil conditions.
(6) Other methods must be found to handle excess.
(7) There will certainly be public opposition to use of radium bearing sludges on farmland.

Farmers in Ohio have purchased 1.87 tons of commercial lime/acre limed/year.[16] Many lands in the same area could utilize 2.7 to 3.5 tons/acre. Liquid sludge (1 to 6 percent solids) could be spread with tank trucks or sprayed; thickened sludge (7 to 15 percent solids) may require pressurized tank trucks; dewatered sludge (20 to 40 percent solids) can be spread by hopper bed trucks.

Uptake of radium by crops is not well understood. If the soil/sludge ratio exceeds 100 to 1, then the added concentration in the soil may approach natural levels of ^{226}Ra in soils. Another consideration would be the future development of farmlands into homesites. A possible concern here would be the build-up of radon daughters in structures built over such lands. The hazard potential would be measured in Working Levels (WL). A home should not exceed 0.01 WL. Appendix F calculates that the worst possible 1 year case, assuming no uptake by vegetation or weathering loss, results in approximately 0.0004 WL. Succeeding years would require less for increasing pH. Most likely, hundreds of years would be required before WL to farmers in their homes reached 0.01 WL.

Utilization as Raw Material

If the lime sludge is dewatered and dried to 20 percent or more solids, other uses could be considered. Several possibilities exist. Dried lime would provide impervious material to stabilize roads, embankments or other consequences of earth moving. Radium content would be a minor problem in those uses. Proposals for use in building materials should be carefully considered in light of the possible release of radon into the environment that the materials will enclose. Mixing with sewage sludge as a disinfectant and deodorant may be very acceptable. Utilization as a neutralizing agent for acid waste would have to be considered in light of the fate of the effluent. Calcination for reuse should be discouraged whenever high radium concentrations are involved.

Disposal

Recharge of deep aquifers with diluted lime sludge was considered. Recharge wells are extremely expensive. Utilization time of recharge well, because of rapid loss of porosity, may be very short.

With prior dewatering of sludges, salt mines would provide the safest method of solving the waste problem. The prevalence of salt mines over large areas of the U.S. makes this an attractive alternative. Salt mines are inherently stable with almost no possibility of leaching by ground waters since any groundwater would have dissolved the salt.

Abandoned mines of other types may be considered. Many problems are immediately evident. Items such as distance, location, depth, safety, ownership, future mining, geology, groundwater, etc. are some of the key words of problems that would have to be addressed.

Treatment of the lime sludge as a nuclear waste was considered. The process would involve some method of dewatering, drying, solidification with cement or other material in 55-gallon drums, shipping, and burial in a controlled site. Cost beyond dewatering, drying and shipping would be expected to exceed $0.04 per 1000 gallons of finished water.

METHODS FOR BACKWASH DISPOSAL

Alternatives for disposal of filter backwash are less than for the lime sludges. Some methods will depend upon location, plant capacity and perational factors. Several of the more important alternatives are listed below.

I. Discharge
    A. Discharge to sanitary sewer
    B. Discharge to local receiving water

II. Storage
    A. Tanks or lagoons
        1) for settling and decanting into receiving water
        2) for settling and pumping supernatant back to plant

III. Disposal as a Nuclear Waste.

Discharge to Sewers

If the backwash from the lime-soda process filters is released to sanitary sewer systems in the same city, the flow will be diluted into the approximately 100 gallons per person per day of sanitary sewage. Therefore, the concentration of radium in the sanitary sewer system prior to treatment would be a function of the radium concentration in the backwash flow. Assume that no settling tanks are provided. The radium concentration in the backwash is a function of the raw water radium concentration (RWR) and whether it exceeds 16 pCi/l. No specific information has been located on the ability of a sewage treatment plant (secondary treatment) to remove radium. However, there are strong indications in the literature that non-essential elements are not removed much greater than 40 percent. This effect is probably more of an absorptive mechanism rather than an assimilative mechanism of uptake. In order to be conservative, the 40 percent removal is used as a model, the equations for the radium concentration in the sewage treatment effluents become as follows:

Sewage treatment plant effluent, radium concentration, pCi/l = 0.027 (RWR-5)

for RWR >16 pCi/l and (Eq. 16)

Sewage treatment plant effluent, radium concentration, pCi/l = 0.0186 (RWR)

for RWR <16 pCi/l. (Eq. 17)

Equation 16 and 17 are combined graphically on Figure 9.

It is obvious from this analysis that the concentration in the sewage treatment effluent will be much less than the guideline of 9 pCi/l discharge limit. If there are any complications caused by putting the backwash materials into the sewage treatment plant, these should be considered from a chemical point of view. The discharge of this effluent to the sewage treatment plant is a viable alternative. The remaining 40 percent of the radium that enters the sewage treatment plant will, of course, exit the plant via whatever means of sludge handling and disposal is utilized. In comparison to the lime-soda sludge, this is not expected to be a serious problem. In most cases, it will probably go to the same location or another sanitary landfill.

Discharge to Receiving Water

The second alternative to be considered for release of backwash is to allow the water to be discharged into a local watercourse. If we assume that the EPA would apply a guideline similar to that imposed upon the phosphate industry, a discharge limit of 9 pCi/l of radium would only allow plants with influent concentrations of 8.7 pCi/l or less to use this alternative. It would be very important to know the current levels of radium in the proposed watercourse. If the river contains radium at about the same magnitude or has the ability to dilute the discharge by an order of magnitude, then this may become a viable procedure. It may also be necessary to make a determination as to whether the river water is used as a drinking water source somewhere downstream and of impact of releases upon that use.

Table 9 lists some river water radium concentrations in the U.S.A. The average concentration is about 0.3 pCi/l with a low of 0.002 and a high at 3.70 pCi/l. It is obvious that in many cases the backwash from a lime-soda process will exceed the concentration in the river. Therefore it is

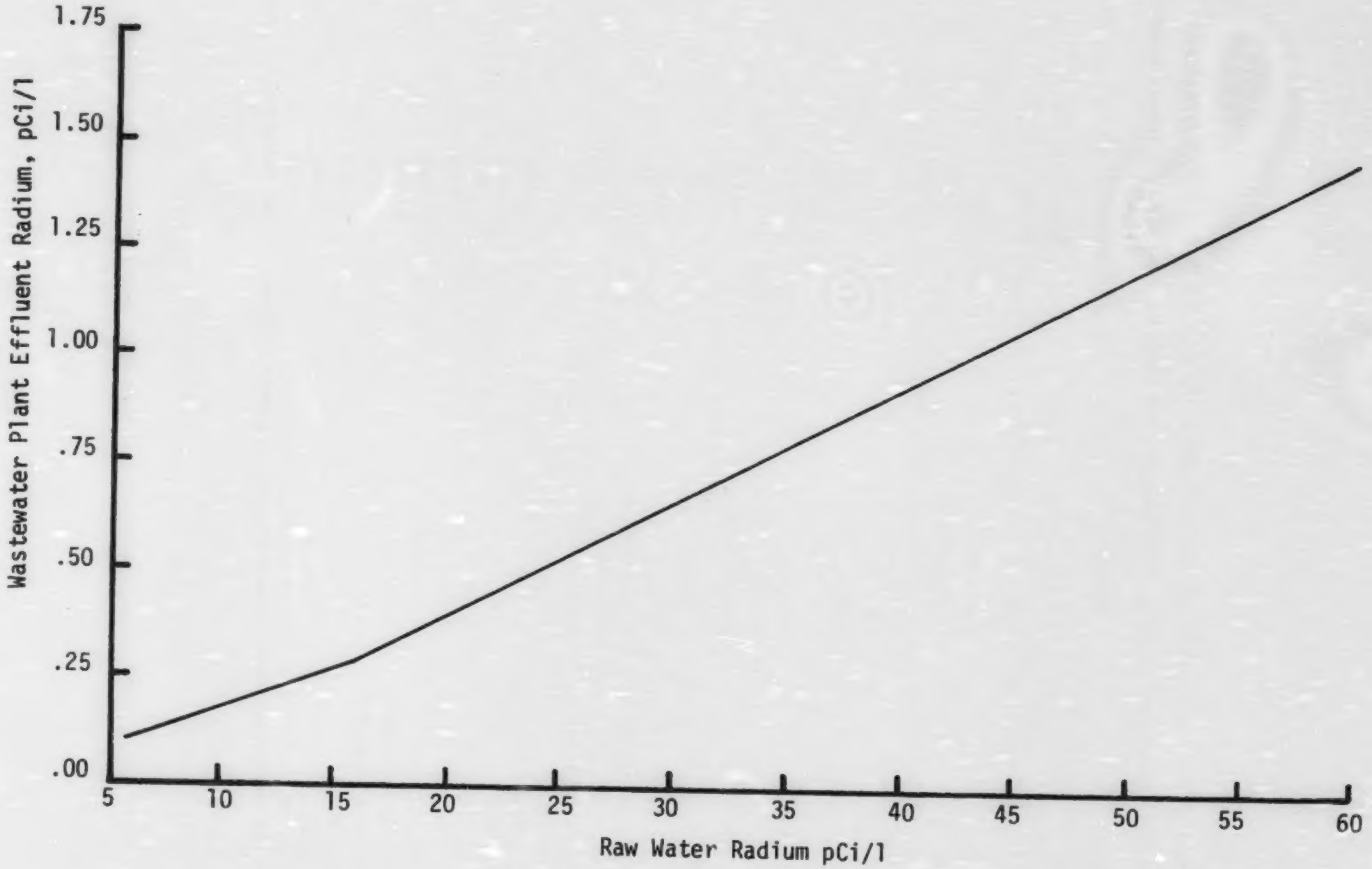


FIGURE 9. RADIUM IN WASTEWATER PLANT EFFLUENT IF BACKWASH OF LIME-SODA PROCESS IS DISCHARGED TO SANITARY SEWERS.

TABLE 9. ≈Ra CONTENT OF SELECTED RIVERS IN THE UNITED STATES

City Supply	Source	Ra Concentration pCi/liter H_2O Raw Water
Atlanta, Ga.	Chattahoochee R.	0.017
Baltimore, Md.	Gunpowder R.	0.020
Birmingham, Ala.	Cahaba R. and L. Purdy	0.024
Bismarck, ND	Missouri R.	0.243
Boston, Mass.	Nashua R.	0.014
Charleston, S.C.	Edisto R.	0.181
Charleston, W. Va.	Elk R.	0.041
Cincinnati, Ohio	Ohio R.	0.061
Denver, Colo.	South Platte R.	0.077
Detroit, Mich.	Detroit R.	0.026
Indianapolis, Ind.	Fall Cr. and White R.	0.137
LaVerne, Calif.	Colorado R.	0.100
Louisville, Ky.	Ohio R.	0.084
Oklahoma City, Okla.	N. Canadian R.	0.106
Omaha, Neb.	Missouri R.	1.770
Philadelphia, Pa.	Delaware R.	0.048
Phoenix, Ariz.	Along Verde R.	0.027
Pittsburg, Pa.	Allegheny R.	3.700
Portland, Ore.	Bull Run R.	0.014
Raleigh, N.C.	Walnut Cr.	0.022
Richmond, Va.	James R.	0.033
Sacramento, Calif.	Sacramento R.	0.018
Salt Lake City, Utah	Cottonwood Cr.	0.034
San Francisco, Calif.	Calaveras Res.	0.018
St. Louis, Mo.	Mississippi R.	1.080
Tacoma, Wash.	Green R.	0.002
Washington, D.C.	Potomac R.	0.033

* Hursh (1953)[2]

necessary to consider the river flow required for dilution.

The river water flow required will be based upon reducing the concentration in the receiving water to 5 pCi/l. Using a mass balance and neglecting the concentration in the river, then

$$\text{River Flow Required, MGD} = 0.9\ (\text{RWR}-5)\ (\text{Pop.}) \qquad \text{(Eq. 18)}$$

for RWR >16

and

$$\text{River Flow Required} = 0.62\ (\text{RWR})\ (\text{Pop.}) \qquad \text{(Eq. 19)}$$

for RWR <16.

Figure 10 shows these equations graphically and demonstrates that there should be little difficulty in finding a receiving water with the necessary dilution.

Holding Tanks, Lagoons and Recycle

The filter backwash flow may be routed to a holding tank or lagoon in order to settle the solids. Holding tank volume should be slightly greater than the volume of backwash water used for filter recycle. Holding tanks are usually about 8' deep. Pump capacity (for discharge or reclamation) will be on the order of twice the average rate of backwash.

The amount of sedimentation achieved in these tanks and lagoons depends upon many factors, including surface area, inlet-outlet design, detention period, agitation, bottom design, and characteristics of the solids. A large fraction of the solids enter the tank in the first few minutes of backwash. The behavior of removed radium in the system is not documented. It is likely that the radium will be fractionated in the same manner as the suspended solids.

Many plants return the settled backwash to the head end of the plant. Without consideration of radium solubility effects, a simple mass balance model would indicate that effluent radium concentrations would initially increase slightly if more than 2 percent of the removed radium is returned to the head end of the plant with a backwash flow of 2 percent of the finished water. The equilibration time is about 5 cycles (or days). The project has assumed that 3 percent of the removed radium will appear in the backwash. Therefore, a holding tank need only to settle one-third of the solids (and radium) in order that recycle will keep the effluent radium concentration equal to the design value. No credit was given for the fact that the radium returned to the head end via this method may be in an insoluble form.

If the holding tank removes more than 33.3 percent of the incoming solids, the concentration of radium in the finished water or the recycle will

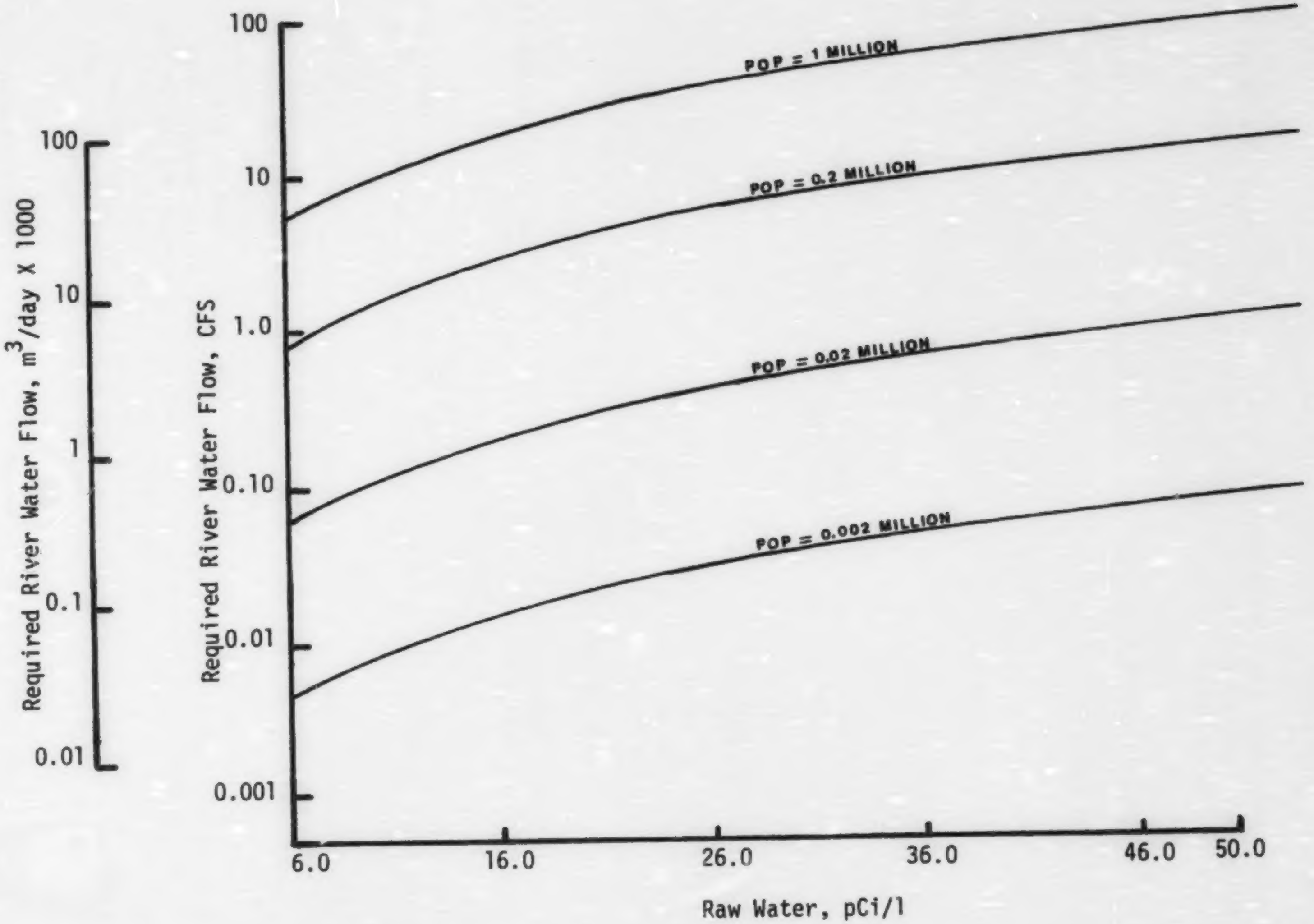


FIGURE 10. APPROXIMATE DILUTION REQUIREMENTS FOR BACKWASH WATER, LIME-SODA PLANTS

theoretically decrease slightly (about 1 percent) and maintain that value after the first five cycles. It is likely that most holding tanks will achieve greater than 50 percent removal of suspended solids. The settled material will have to be handled in the same manner chosen for the lime sludge.

In a few cases the material in the holding tank may be deliberately agitated in order to provide a uniform concentration of solids or radium to discharge into a receiving water. This practice should be weighed against the advantage of including the holding tank sludge with the treatment method chosen for the lime sludge.

Treatment as a Nuclear Waste

If the lime sludge of a plant were treated as a nuclear waste as previously discussed, the backwash could be included in the process for an additional cost of about 3 to 5 percent of the overall cost. Holding tank capacity could be expanded to a size necessary to achieve 85 to 95 percent removal. Coagulation aids would be used. The product sludge would then be routed to the same processes designed for the lime sludge, i.e. dewatering, drying, fixation, transportation, and burial.

COST OF LIME-SODA TREATMENT

Figure 11 shows the capital cost for lime-soda treatment plants, both horizontal flow and upflow solids contact units. Capital costs of such plants are primarily a function of hydraulic design capacity and are not sensitive to the radium or hardness content of the raw water. The range indicated by the figure includes capital costs for all raw water conditions assumed in Table 1. These costs include costs of waste stream handling but not waste stream disposal which are estimated later in this chapter.

Figures 12 through 14 show the annual operating and maintenance costs of lime-soda treatment plants. Those operating costs are a function of raw water quality, both hardness and radium, as well as plant capacity. Annual and operating costs are shown for each of three raw water radium levels over the range of raw water total hardness presented in Table 1; upflow solids. These costs include costs of waste stream handling but not ultimate disposal, which will be considered separately. Unit costs of treatment are discussed in the unit costs section, Section IX.

COST OF LIME-SODA WASTE STREAM DISPOSAL

The dilemma facing the water industry today, and the design engineer in particular, is that the best practicable control technology currently available does not provide reasonable solutions for all water plant waste treatment situations. These solutions are not reasonable for plants in certain water production categories and for plants with unusual raw water characteristics, since the available waste treatment methods could impose extreme changes in treatment operations, or inordinate increases in water production costs.

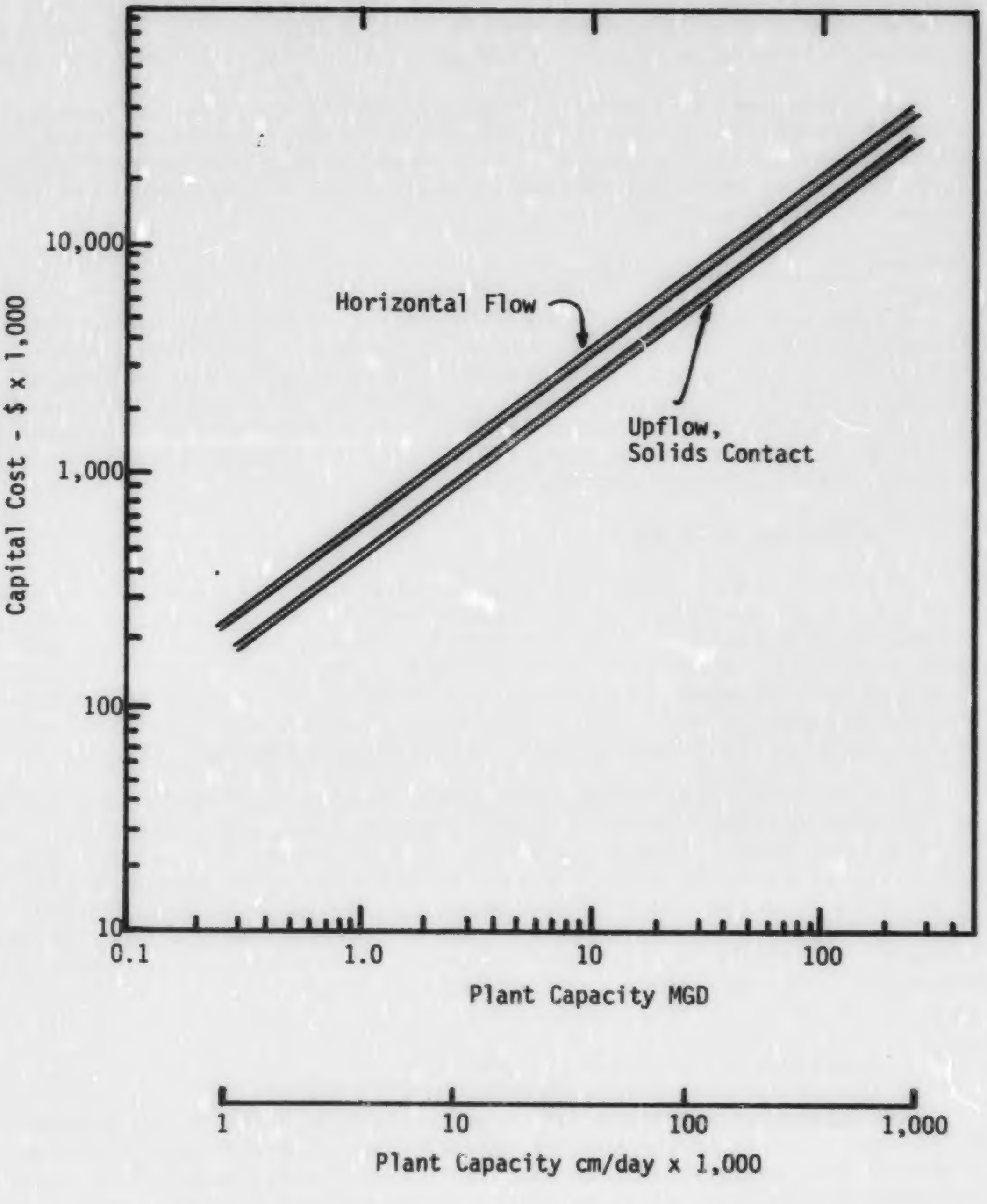


FIGURE 11. CAPITAL COSTS FOR LIME-SODA TREATMENT

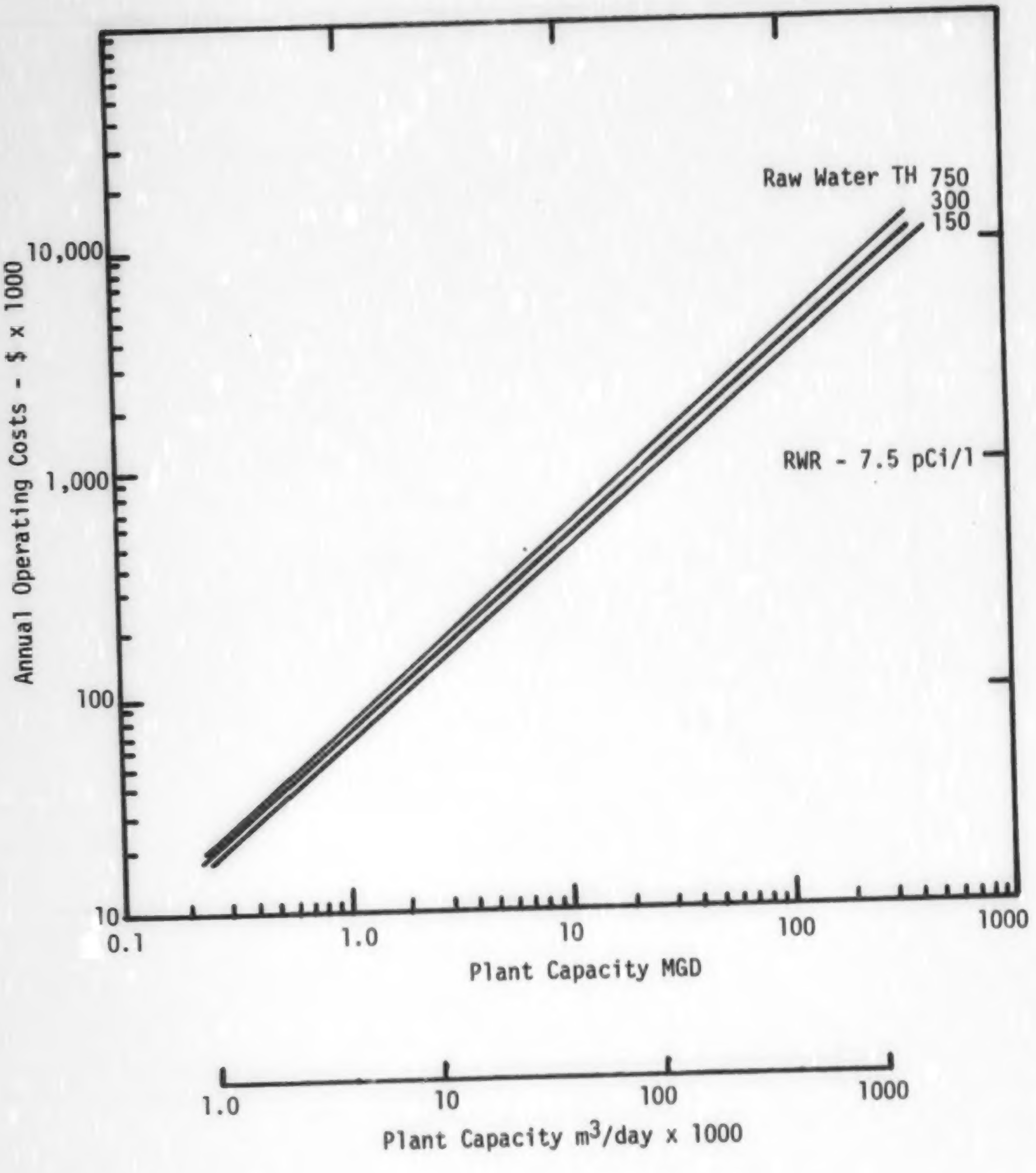


FIGURE 12. ANNUAL OPERATING COSTS, LIME-SODA PROCESS, RWR 7.5 pCi/l.

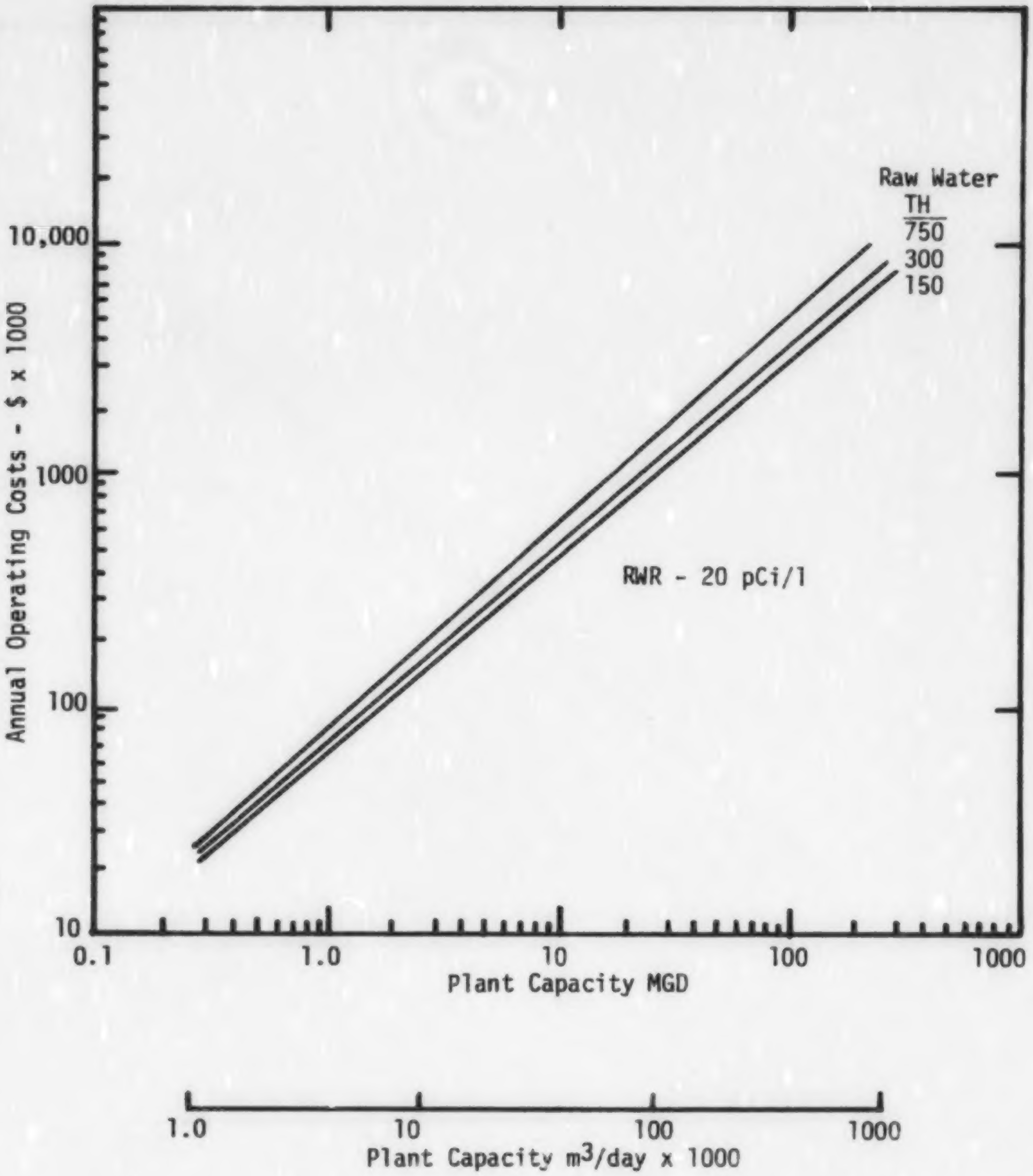


FIGURE 13. ANNUAL OPERATING COSTS LIME-SODA PROCESS, RWR - 20 pCi/l

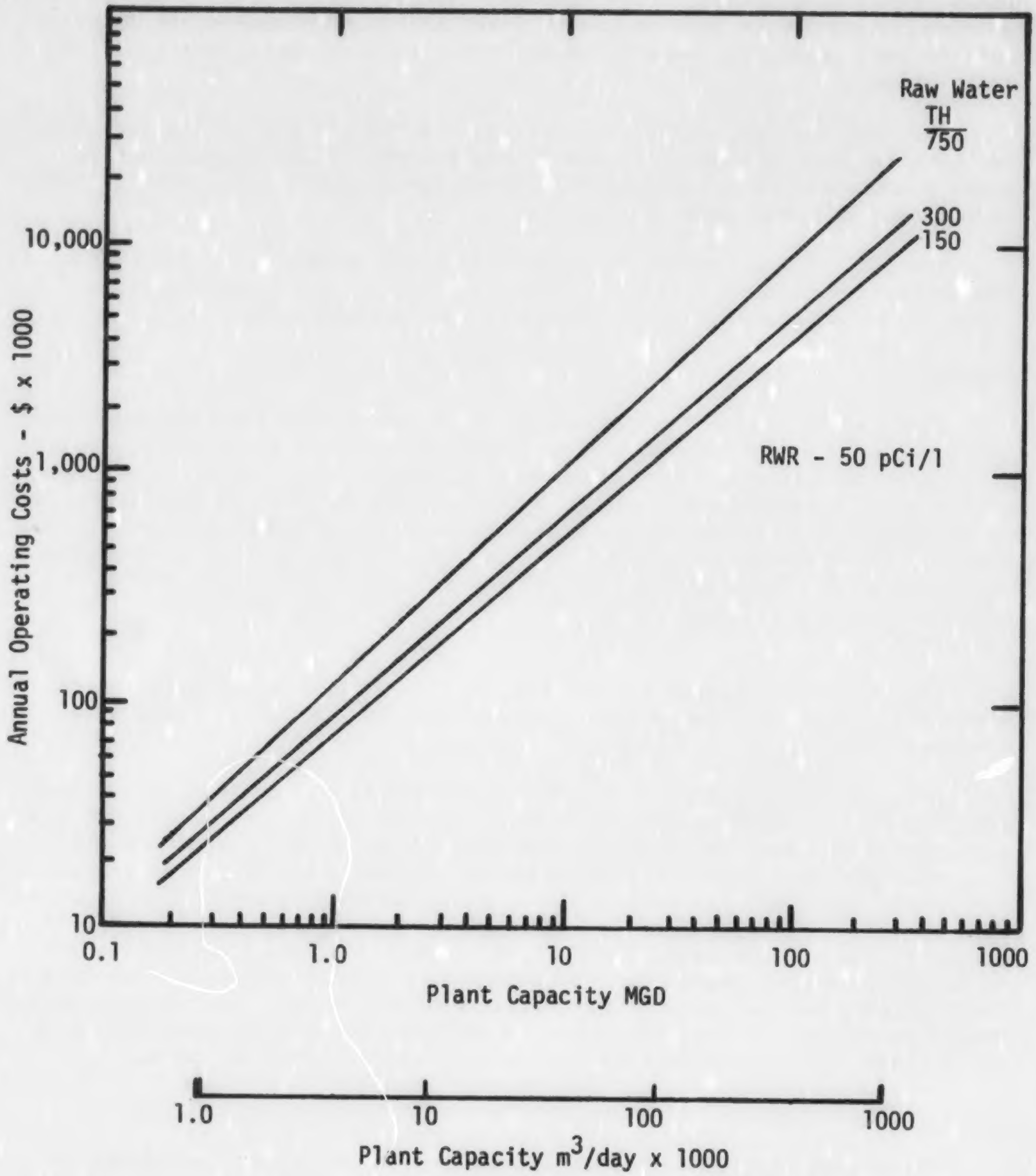


FIGURE 14. ANNUAL OPERATING COSTS LIME-SODA PROCESS, RWR - 50 pCi/l

Given the wide range of raw water characteristics, sludge production rates, physical-chemical sludge characteristics, and numerous other variables and constraints which face community water treatment planners, it is difficult to make meaningful cost estimates for treatment and disposal of lime-soda sludges.

The main problem facing small plants, 10 MGD (37,850 m^3/day) or less, is the high cost of mechanical dewatering equipment. This equipment is usually economically out of reach to these small plants. Lagoons are their most frequently used solution.

The main problem facing large plants, above 10 MGD or 37,850 m^3/day, is the problem of finding sufficient landfill facilities to accommodate the large volume of waste solids produced by the lime-soda process.[17]

Lagoons

There are two types of lagoons which can be utilized for disposal of lime-soda sludges, thickening and storage lagoons, and permanent lagoons. Thickening and storage lagoons are used to concentrate the liquid sludge solids by long term gravity settling to 25-40 percent dry solids by weight. The dried sludge is then removed by draglines or other loading equipment to a landfill or other ultimate disposal location. Permanent lagoons are used for final disposal of sludge. In permanent lagoons the liquid sludge is spread in thin layers and allowed to concentrate to an ultimate solids concentration of about 70 percent.

The permanent lagoons are allowed to fill up over a period of years; when full, they are covered with fill and the land reclaimed for limited purposes.

Based on a loading rate of 100 lbs solids/sq. ft./cycle (.45 hectares per 1000 m^3), a lagoon depth of 5 feet, a construction cost of $14,000 per acre including land, and a three-year cycle time for thickening and storage lagoons, the unit costs of thickening and storage lagoons are very small, for plants of 10 MGD capacity or less, being approximately $.01/1000 gallons. Cost of ultimate disposal of the dried sludge after its removal from temporary storage is discussed later in the report. Figure 15 gives the unit costs of a permanent lagoon for ultimate disposal of lime-soda sludge as a function of plant capacity. This estimate is based on a loading rate of 3.0 pounds solids/sq. ft./ft. of lagoon depth/year, depth of 8 feet, fill time of 20 years, and a construction and land cost of $14,000 per acre.

Gravity Thickening

Thickening calcium carbonate sludges by gravity alone can result in considerable increase in solids content. The typical gravity thickener consists of a round holding tank usually provided with rotating sludge scrapers and is designed to provide sufficient detention time to allow solids to concentrate to the desired level. Economically achievable concentrations of dry solids for a lime-soda sludge range from about 7 to 15 percent as dry solids. Figure 16 shows the unit costs for a typical gravity

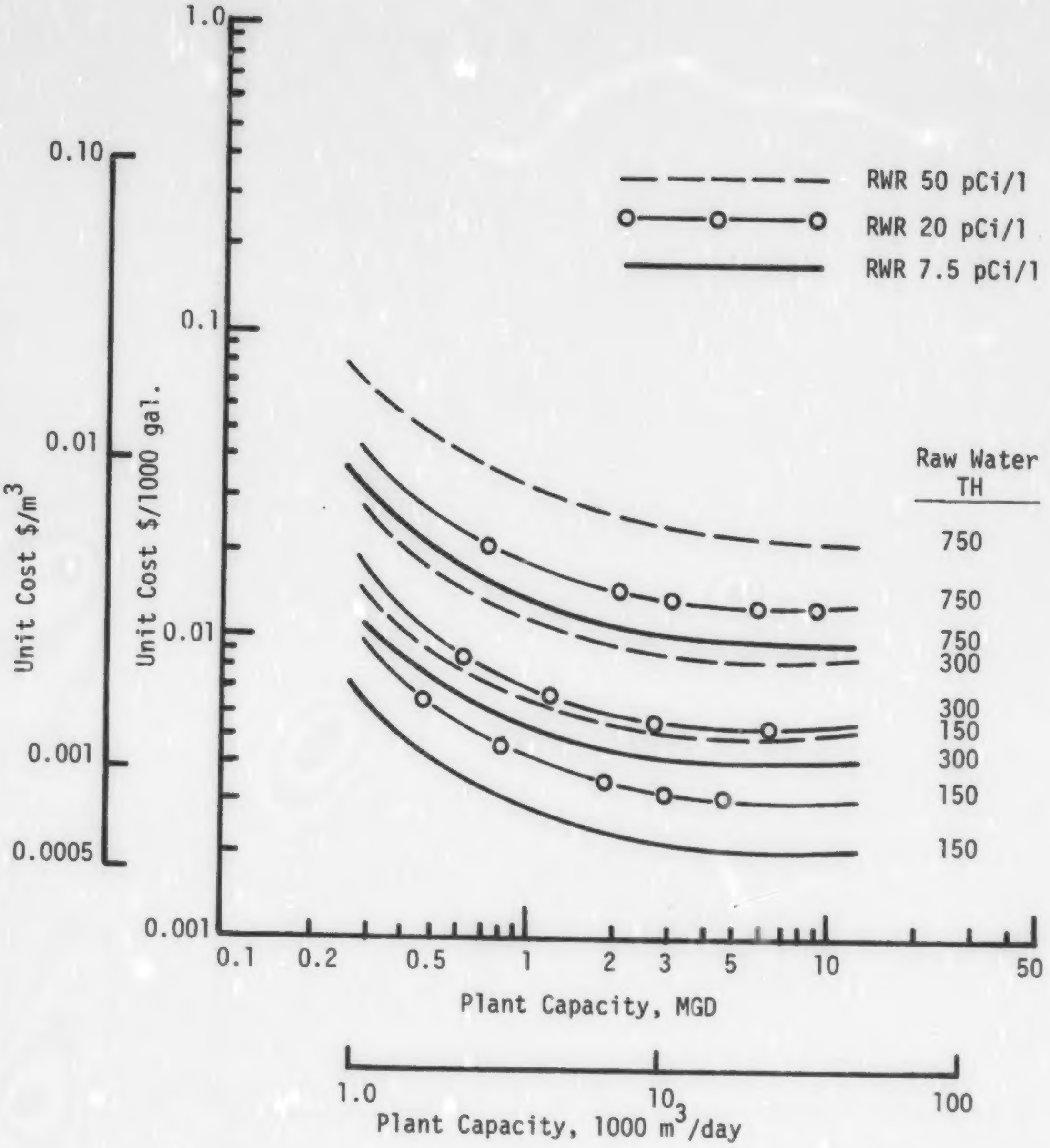


FIGURE 15. UNIT COST OF PERMANENT LAGOONS, LIME-SODA PLANTS 10 MGD AND UNDER.

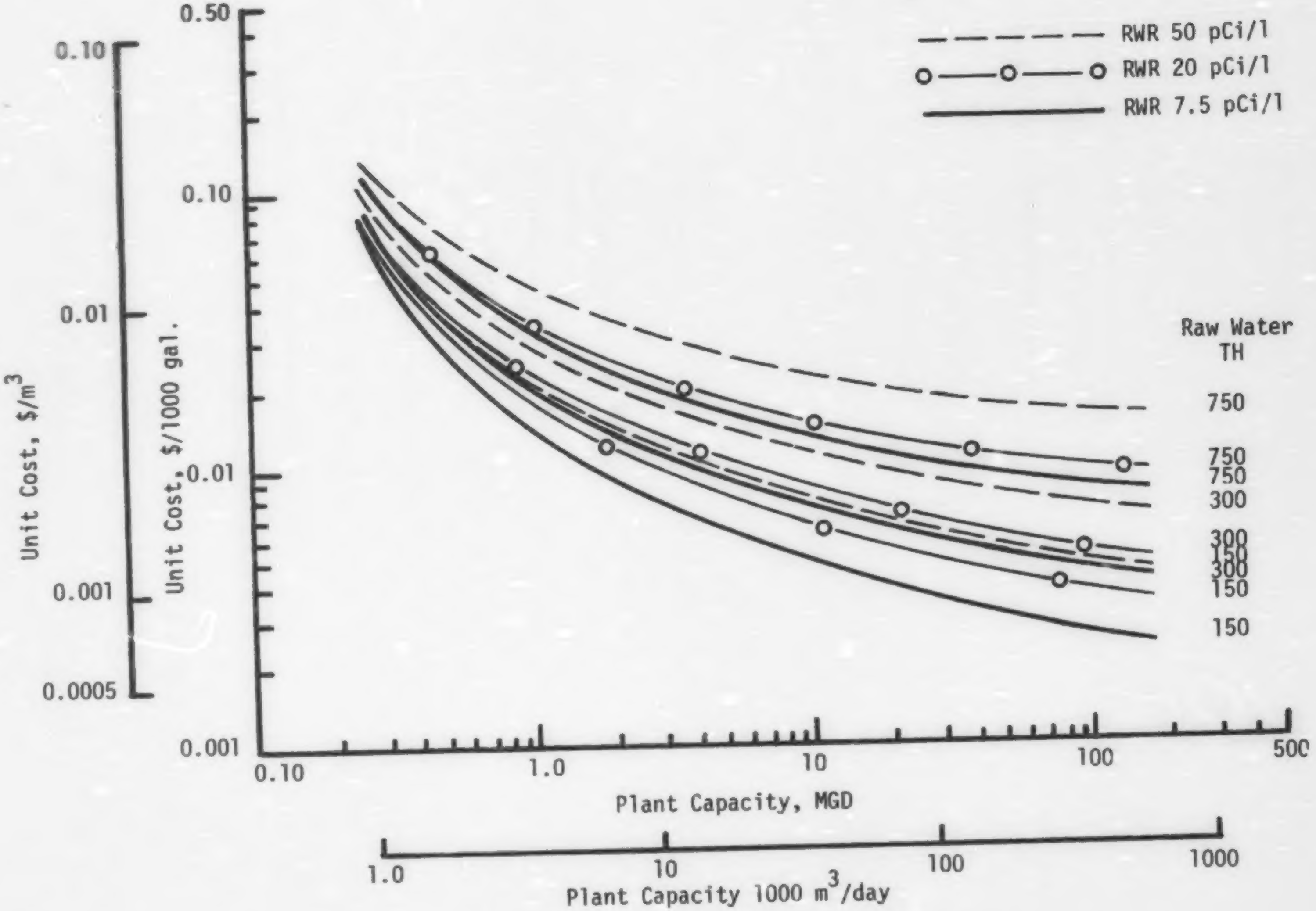


FIGURE 16. UNIT COST OF GRAVITY THICKENING, LIME-SODA SLUDGE

thickener. The low unit cost of gravity thickening makes this process quite cost effective if the sludge is to be transported or mechanically dewatered later on in the sludge handling process.

Mechanical Sludge Dewatering

The methods used to remove sufficient water from liquid sludges so as to change the physical form to that of a damp solid are best described in terms of the particular type of dewatering device used. The commonly used devices include:

(1) Rotary vacuum filters
(2) Centrifuges
(3) Filter presses
(4) Horizontal belt filters.

The relationship of the various dewatering methods to those processes which immediately precede and follow them are summarized in Table 10.

An ideal dewatering operation would capture practically all the solids in the dewatered cake at minimum cost. The resultant cake would have the physical handling characteristics and moisture content optimal for subsequent processing. Process reliability, ease of operation, and compatibility with the plant environment would also be optimum.

Dewatering costs are extremely variable due to differences in sludge characteristics, plant size, and location. Table 10 lists the cost range for mechanical dewatering systems in $/ton of dry solids. As previously mentioned, mechanical dewatering is usually limited to plants over 10 MGD in capacity for reasons of scale economics. The unit cost of mechanical sludge dewatering is a function of daily sludge production as well as cost of equipment and conditioning chemicals. The unit cost can be quite variable and no attempt will be made here to graphically portray this cost due to the very limited amount of cost data available on the subject. Unit cost of mechanical sludge dewatering equipment ranges between $.02 and $.15 per 1000 gallons of finished water depending upon raw water hardness and raw water radium content. A good average figure for rough estimation would be $.05 per 1000 gallons.

The technology and design of all available dewatering methods has been constantly under development, particularly in the past five years. Each type, therefore, should be given careful consideration. The applicability of a given method should be determined on a case-by-case basis with the specifics of any given situation being carefully evaluated, preferably in pilot tests.[19] For further discussion of the theory and design of mechanical dewatering methods see the Environmental Protection Agency Process Design Manual, Sludge Treatment and Disposal, Chapter 7.[18]

Landfill

Ultimate disposal by landfill involves two major cost elements: the cost of transportation of the sludge to the landfill and the cost of landfill

TABLE 10. THE RELATIONSHIP OF DEWATERING TO OTHER SLUDGE TREATMENT PROCESSES FOR TYPICAL MUNICIPAL SLUDGES[18]

Method	Pretreatment Normally Provided		Normal Use of Dewatered Cake		Approximate Cost $/ton Dry Solids
	Thickening	Conditioning	Landfill	Land Spread	
Rotary Vacuum Filter	Yes	Yes	Yes	Yes	12 - 25
Centrifuge (Solid Bowl)	Yes	Yes	Yes	Yes	20 - 30
Centrifuge (Basket)	Variable	Variable	No	Yes	20 - 30
Filter Presses	Yes	Yes	Yes	Variable	18 - 27
Horizontal Belt Filters	Yes	Yes	Yes	Yes	20 - 30

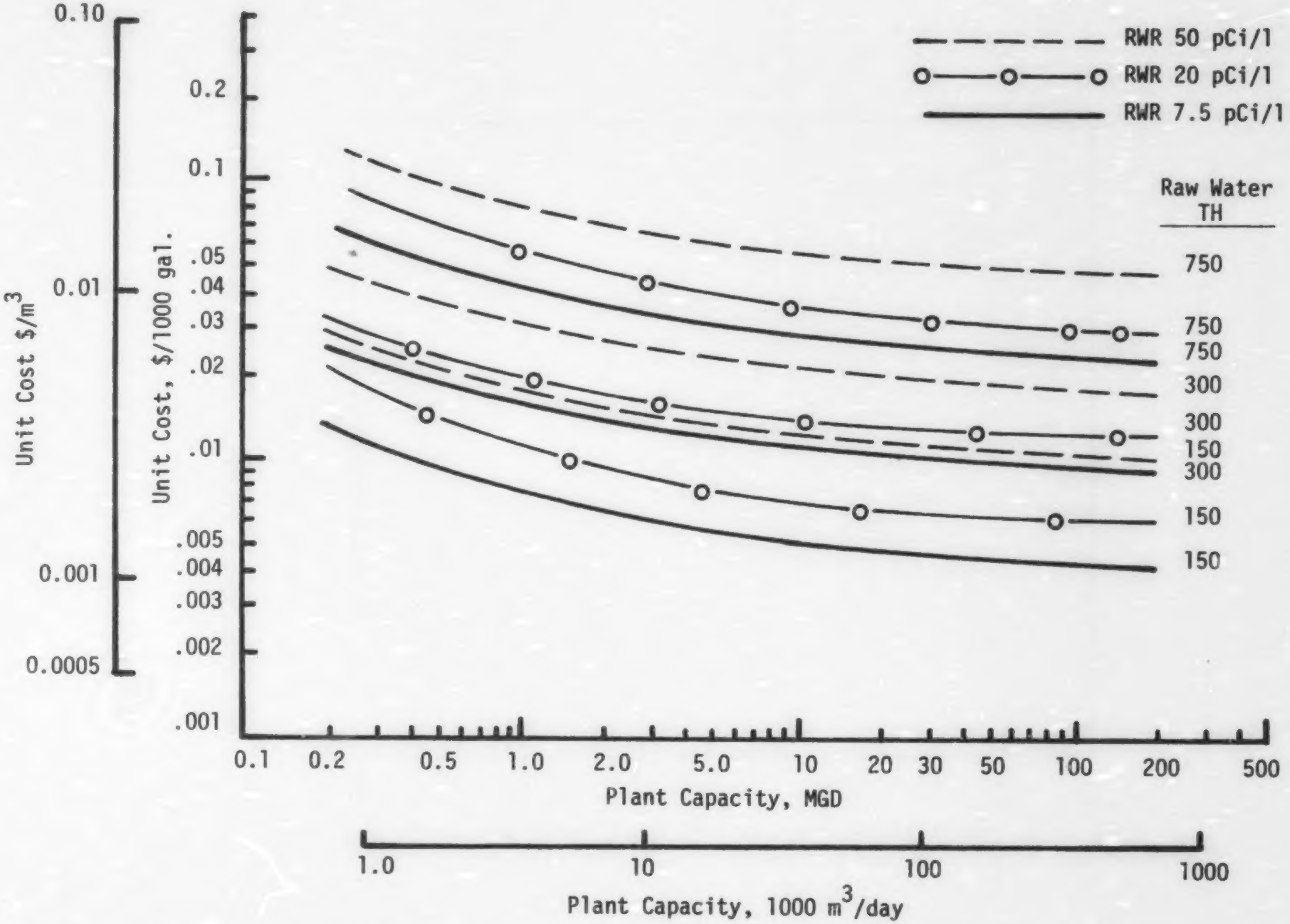


FIGURE 17. UNIT COST OF TRANSPORTING 10% SOLIDS LIME-SODA SLUDGE BY TRUCK OVER A 5-MILE ONE-WAY HAUL

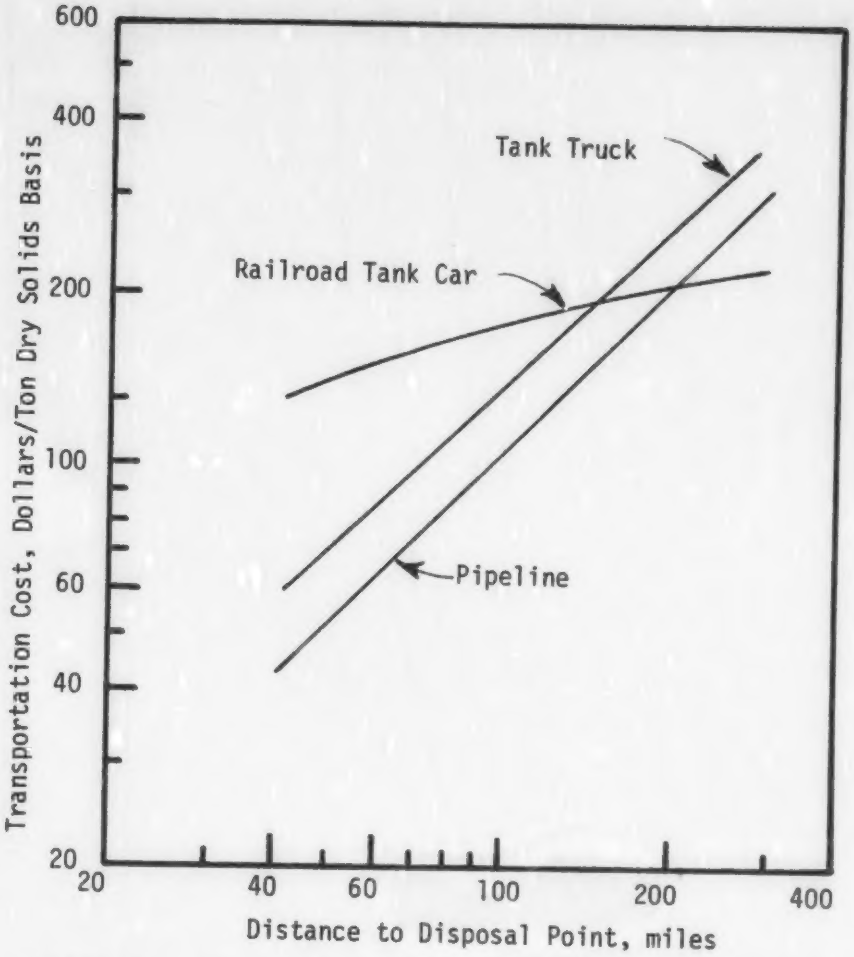


FIGURE 18. RELATIVE TRANSPORTATION COST FOR LIQUID ORGANIC SLUDGES [18]

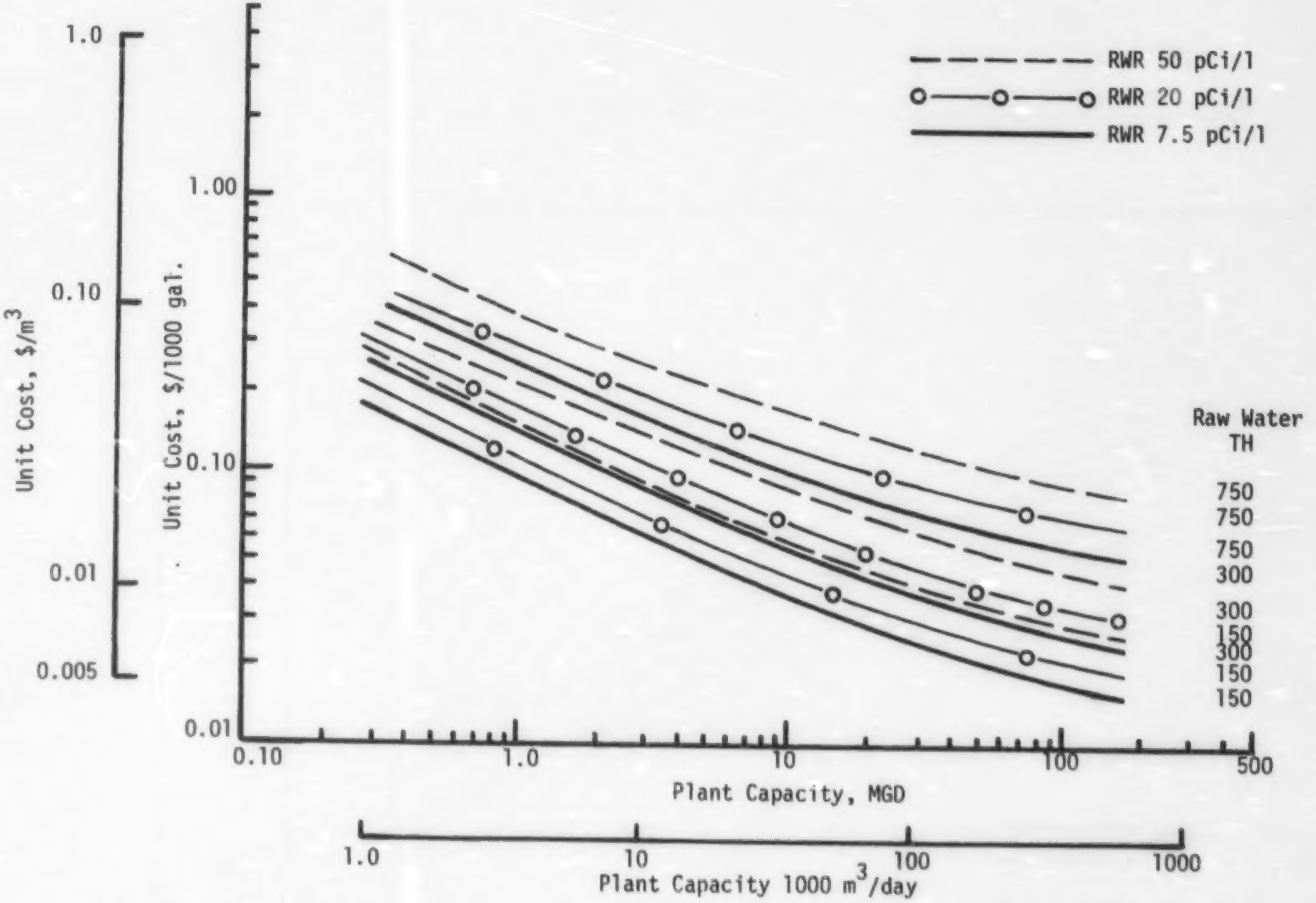


FIGURE 19. UNIT COST OF SANITARY LANDFILL, 10% SOLIDS LIME-SODA SLUDGE

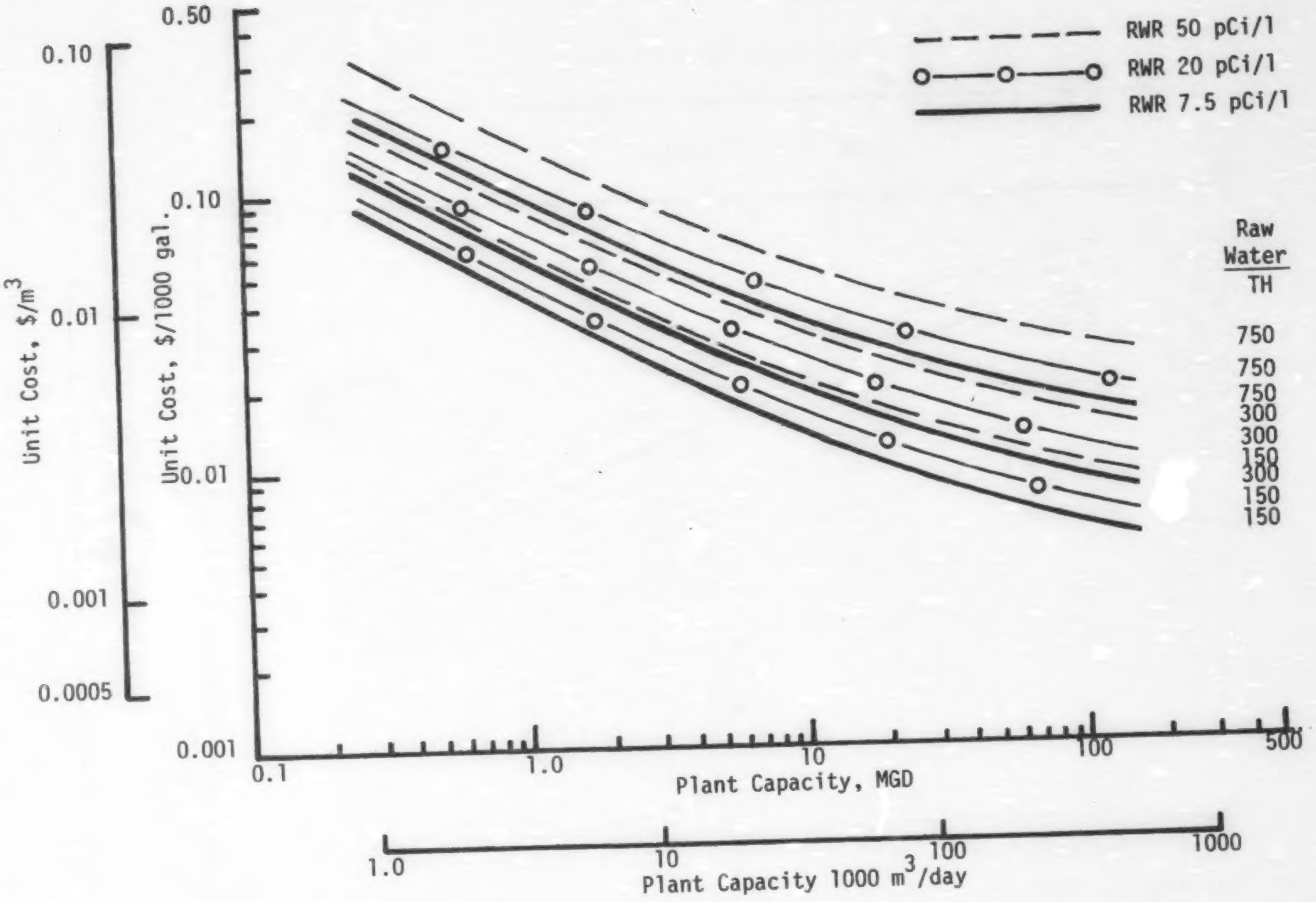


FIGURE 20. UNIT COST OF SANITARY LANDFILL, 50% SOLIDS LIME-SODA SLUDGE.

operation itself. Sludge can be transported by truck, rail, or pipeline in liquid form (up to about 6 percent solids), thickened condition (up to about 15 percent solids), or dewatered condition (above 25 percent solids - truck or rail only).

Generally speaking, the economics of sludge disposal improve (1) if sludge volume is reduced by removing water, (2) per unit basis as volume of sludge increases, and (3) if sludge can be sold to reduce operating costs.

Figure 17 shows the unit costs of transporting thickened sludge (10 percent solids) by truck over a five mile (one-way) haul, based on a typical hauling cost of $6.00 per ton solids. Figure 18 is a comparison of transportation costs of pipeline, tank truck, and rail hauling for long distance hauls of liquid sludge (about 5 percent solids). It can be seen from this figure that railroad hauling becomes more economical than truck hauling at a distance of about 150 miles. Pipeline transportation is the least expensive of all the transportation methods up to a distance of about 200 miles, however, the large capital cost of pipeline and their inherent lack of flexibility in terms of disposal location makes this alternative less favorable for most applications.

The unit costs for construction and operation of sanitary landfills are shown in Figures 19 and 20. Figure 19 is for sludge of 10 percent solids and Figure 20 is for sludge of 50 percent solids.

Costs of spreading sludge on farmland, disposal in strip mine areas, etc. are extremely variable and can best be estimated by the planner using transportation costs from Figures 17 and 18, and sanitary landfill costs from Figure 19 and 20. Adjustments can be made to the construction cost of the landfill if development costs of farmland, spreading, and strip mine disposal are known.

SECTION VII

ION EXCHANGE SOFTENING

GENERAL

Water softening by the ion-exchange process depends upon the ability of certain insoluble substances to exchange cations with other cations dissolved in water. When a hard water is passed through a sodium cation exchanger, the calcium and magnesium in the hard water are replaced by sodium for the exchanger; and because this reaction is reversible, after all of the readily replaceable sodium has been exchanged for calcium and magnesium from the hard water, the "exhausted" cation exchanger can be regenerated with a solution of sodium chloride (common salt). In the regeneration process, the calcium and magnesium of the exhausted cation exchanger are replaced with a fresh supply of sodium from the regenerating brine solution. Then, after a washing with water to free it from brine, the regenerated exchanger is ready to soften a fresh supply of hard water[23].

Various materials with cation exchange properties, some naturally occurring and some synthetic, are used as exchange media for softening by ion exchange. The most widely used materials, however, are the various forms of synthetic styrene divinyl benzene copolymer resins which possess large exchange capacities, resistance to dissolution over a wide pH range, and great mechanical strength. The typical polystyrene type resin has an exchange capacity in the range of 18,000 to 30,000 grains of hardness per cubic foot of material. The capacity of the resin is a function of the amount of salt used in regeneration. For example, a resin with a capacity of 24,000 grains of hardness per cubic foot when regenerated with 0.25 lb. of salt per 1,000 grains of hardness removed will have an increased capacity of 30,000 grains when regenerated with twice the amount of salt. Economic considerations are the controlling factor when balancing capacity with amount of salt used in regeneration. The concentration of the salt solution used in regeneration also plays an important role in determining the exchange capacity of the media. Media regenerated with sea water or connate brines are not as high in capacity as when regenerated with a concentrated salt solution.

The generalized chemical reactions of the cation-exchange process are as follows:

a) Softening

$$Ca^{++} + 2NaR \rightarrow CaR_2 + 2Na^+$$

$$Mg^{++} + 2NaR \rightarrow MgR_2 + 2Na^+$$

b) Regeneration

$$CaR_2 + 2Na^+ \rightarrow Ca^{++} + 2NaR$$

$$MgR_2 + 2Na^+ \rightarrow Mg^{++} + 2NaR \qquad \text{(Eq. 19-A)}$$

Hardness removal in an ion-exchange unit is essentially complete (approaching 100 percent). High sodium levels in the raw water, incomplete rinsing of the media during regeneration, and other practical considerations can cause "leakage" of a few parts per million calcium and magnesium ions so that hardness removal is usually somewhat less than 100 percent.

Polystyrene resin exchange media are also capable of being regenerated by strongly acid solutions. The exchanger is then said to operate in the hydrogen cycle. In the hydrogen cycle the hardness cations exchange with a hydronium ion, thereby neutralizing some of the alkalinity of the treated water and decreasing pH. Water treated by the hydrogen cycle is usually blended with raw water in "split treatment" in order to adjust the pH of the treated water. Split treatment is used in only a few specialized locations in the United States and will not be discussed further in this report.

The advantages of ion-exchange softening are:

1) Ease of operation and control. Many I/X plants are completely automated reducing need for labor.

2) Finished water hardness can be closely controlled by blending treated water with raw water in varying amounts.

3) Costs can be held quite low for small plants.

4) Treated water alkalinity is not affected by sodium cycle operation.

5) Trace amounts of heavy metals, as well as radium, are easily removed.

Some disadvantages of the I/X process are:

1) Finished water shows an actual increase in total dissolved solids since one calcium ion of atomic weight 40 is replaced by two sodium ions of total atomic weight 46.

2) Sodium concentrations can be elevated above recommended concentrations for control of hypertension and cardiovascular diseases.

3) Raw water requires pretreatment if considerable amounts of turbidity and suspended solids, iron and manganese, or bacterial slimes are present.

4) Finished water may be corrosive in distribtuion lines unless some form of stabilization is practiced.

5) Disposal of spent brines can be problematic. Regulatory agency approval is often difficult to obtain.

An ion-exchange water softening unit resembles an ordinary mechanical sand filter with ion exchange mineral substituted for sand. This filter may be the pressure type device or the open gravity type similar to those used at large water purification plants. The pressure softener consists of a closed steel cylinder which may be of the vertical or horizontal type. If tanks are to be shipped assembled, the diameter must be limited to about 10 to 11 feet because of shipping regulations. There are a number of 14-foot steel welded units in operation. Gravity or open-top softeners usually are built of concrete and are rectangular in shape, although some round steel units have been built. The pressure type has one advantage over the open-type softener in that it is possible to pump the water to be softened directly from the source of supply through the softener into the distribution system, thus obviating double pumping. Gravity filters have an advantage in that it is possible to observe their condition readily, and to see whether or not there is any channeling of the water or brine through the bed, or any mineral being washed out.[24] Figure 21 shows a typical ion-exchange softening system.

RADIUM REMOVAL IN THE ION EXCHANGE PROCESS

Table 11 lists radium removal efficiencies and associated hardness removal efficiencies for ion-exchange plants. Figure 22 portrays this information graphically. It is readily seen that radium is removed with high efficiency by the ion-exchange process. The plants whose radium removal efficiencies were less than 90 percent were those whose plant operation was characterized by either operation past normal breakthrough or incomplete regeneration of the resin. It should be noted that some of the plants listed in Table 11 included iron and manganese removal as pretreatment prior to ion exchange. This was usually accomplished by aeration and filtration. Although these processes were successful in reducing iron and manganese, reduction of radium in pretreatment was insignificant and will not be further discussed.

It is interesting to note that radium is removed with greater efficiency than calcium or magnesium. There also appears to be a built-in safety factor in that radium continues to be removed with a fairly high efficiency, ≈85 percent removal, even after hardness breakthrough occurs.

For purposes of this report, a 95 percent radium efficiency removal at 95 percent total hardness removal was chosen at the practically achievable result in a well designed and operated ion exchange plant.

REQUIRED TREATMENT FRACTION

Figure 23 indicates the overall schematic of an ion-exchange plant. The basic design considers a bypass fraction and a treated fraction which are reblended to achieve the required water quality. When both total-hardness removal and radium removal are assumed to be 95 percent, the fraction of raw water to be treated in the ion exchanger to achieve a finished-water concentration of 5 pCi/l can be calculated as a function of raw water radium concentration

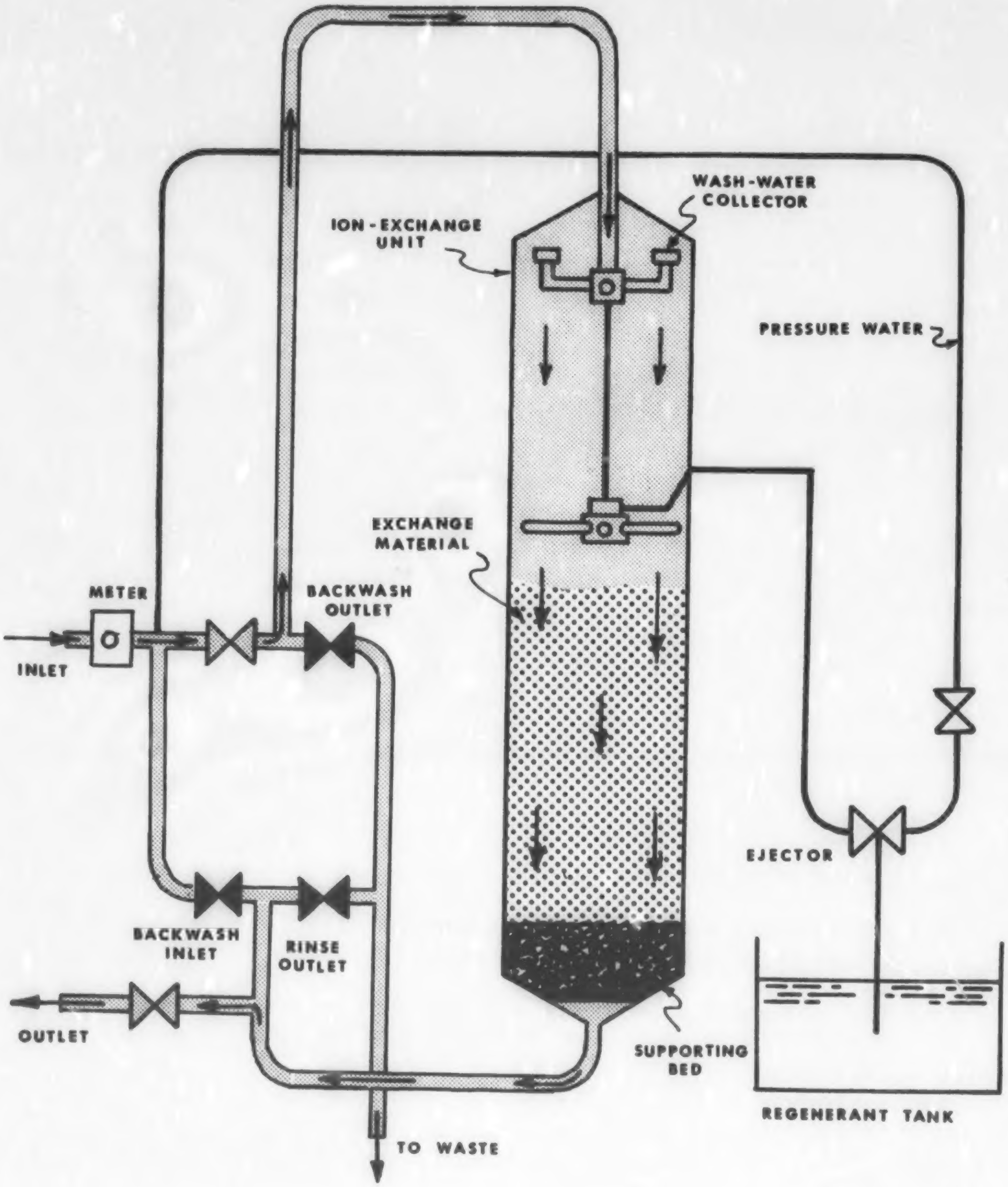


FIGURE 21. DIAGRAM OF TYPICAL ION EXCHANGE UNIT

TABLE 11. RADIUM REMOVAL IN ION EXCHANGE PLANTS

Plant	Ra in pCi/l	Ra out pCi/l	% Ra Rem.⁰	TH in mg/l$CaCO_3$	TH out mg/l$CaCO_3$	% TH Rem.⁰
Eldon, IA	49	1.9	96	375	10	97
Estherville, IA	5.7	0.3	95	915	46	95
Grinnell, IA	6.7	0.2	97	385	11	97
Holstein, IA	12	0.5	96	920	18	98
Dwight Corr. Inst., IL	3.26	0.36	89	286	43	85*
Herscher, IL	14.31	1.31	91	406	60	85*
Lynwood, IL	14.69	0.41	97	848	78	91
Sarasota, FL	4.3	0.70±	84	460	159±	65**

⁰ Removed

± Adjusted to take account of raw water blending.

* % hardness and % Ra removals are somewhat low due to breakthrough occurring prior to all samples being collected.

** % hardness and % Ra removals are somewhat low due to incomplete regeneration of media as 1/2 brine pumping capacity was down for repair.

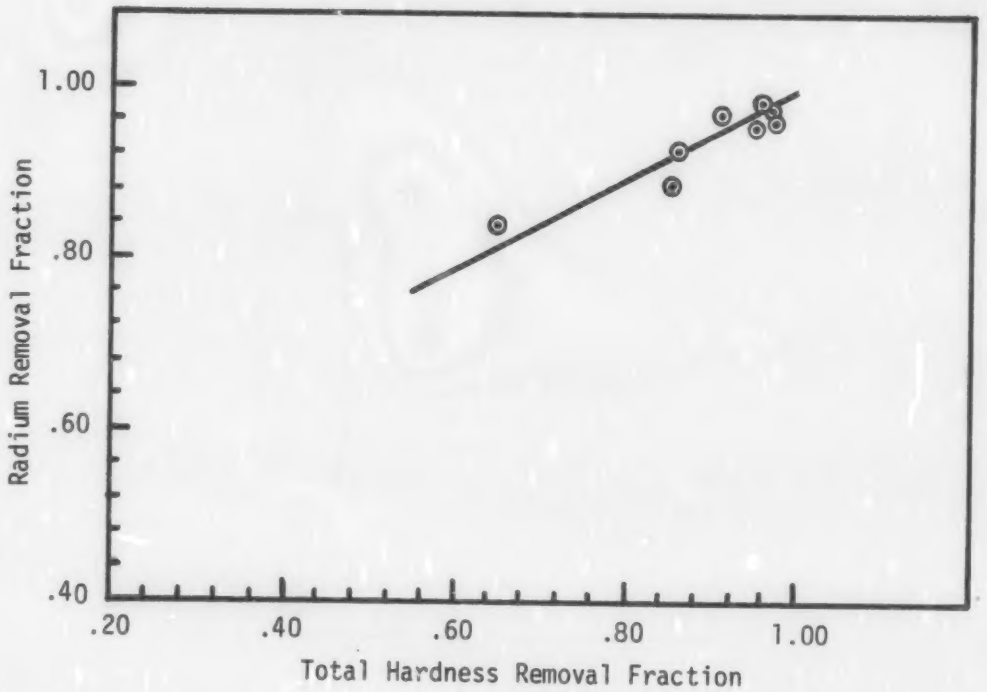


FIGURE 22. RADIUM REMOVAL FRACTION VS. TOTAL HARDNESS REMOVAL FRACTION IN ION EXCHANGE PLANTS (BEFORE BLENDING)

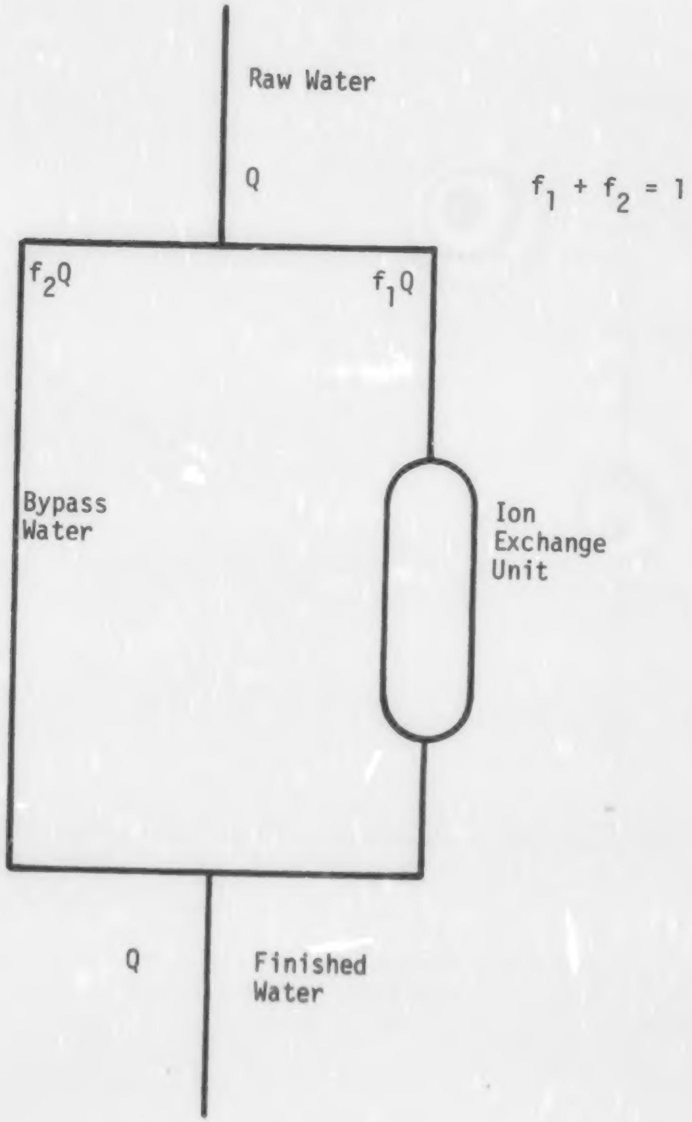


FIGURE 23. MASS BALANCE FOR DETERMINING FRACTION OF RAW WATER TO BE TREATED

and is portrayed in Figure 24. The fraction of raw water blended is one minus the fraction treated.

A mass balance to achieve a finished water at 5 pCi/l yields

$$\text{Fraction Treated} = 1.053\ (1 - (5/\text{RWR})) \qquad \text{(Eq. 20)}$$

Design and costs calculations for ion exchange were based on the above mentioned premise that finished-water concentration of radium would equal the limit of 5 pCi/l. It is again to be noted that many communities may desire water treated to a greater degree of hardness removed for aesthetic or health reasons. Further treatment would increase the costs above those listed in this report.

The lifetime of the unit depends upon its size and upon the total hardness to be removed. The populations to be served range from 100 to 50,000 people. This project will assume a flow of 150 gpcd and three hardness levels as in previous calculations.

BRINE PRODUCTION

The total volume of wastewater generated is a direct function of the total hardness and the volume treated. See Figure 25. Mathematically,

$$\text{Total Wastewater Rate (brine and rinse)} = 105\ \text{TH, gal/MG} \qquad \text{(Eq. 21)}$$

The best available data[11] indicate that 78 percent of the removed radium goes to the brine solution effluent and 13 percent comes out in the backwash. This report will assume that 91 percent of the radium removed from the treated stream will be mixed into the total wastewater flow of backwash and brine combined. The remaining 9 percent must remain on the resin and a build-up occurs with this model.

The resulting concentration of radium in the total wastewater will be:

$$\text{Wastewater Radium Concentration, pCi/l} = \frac{9524\ (\text{RWR} - 5)}{\text{Total Hardness, mg/l}} \qquad \text{(Eq. 22)}$$

for RWR > 16 pCi/l

$$\text{Wastewater Radium Concentration, pCi/l} = \frac{6572\ (\text{RWR})}{\text{Total Hardness, mg/l}} \qquad \text{(Eq. 23)}$$

for RWR < 16 pCi/l

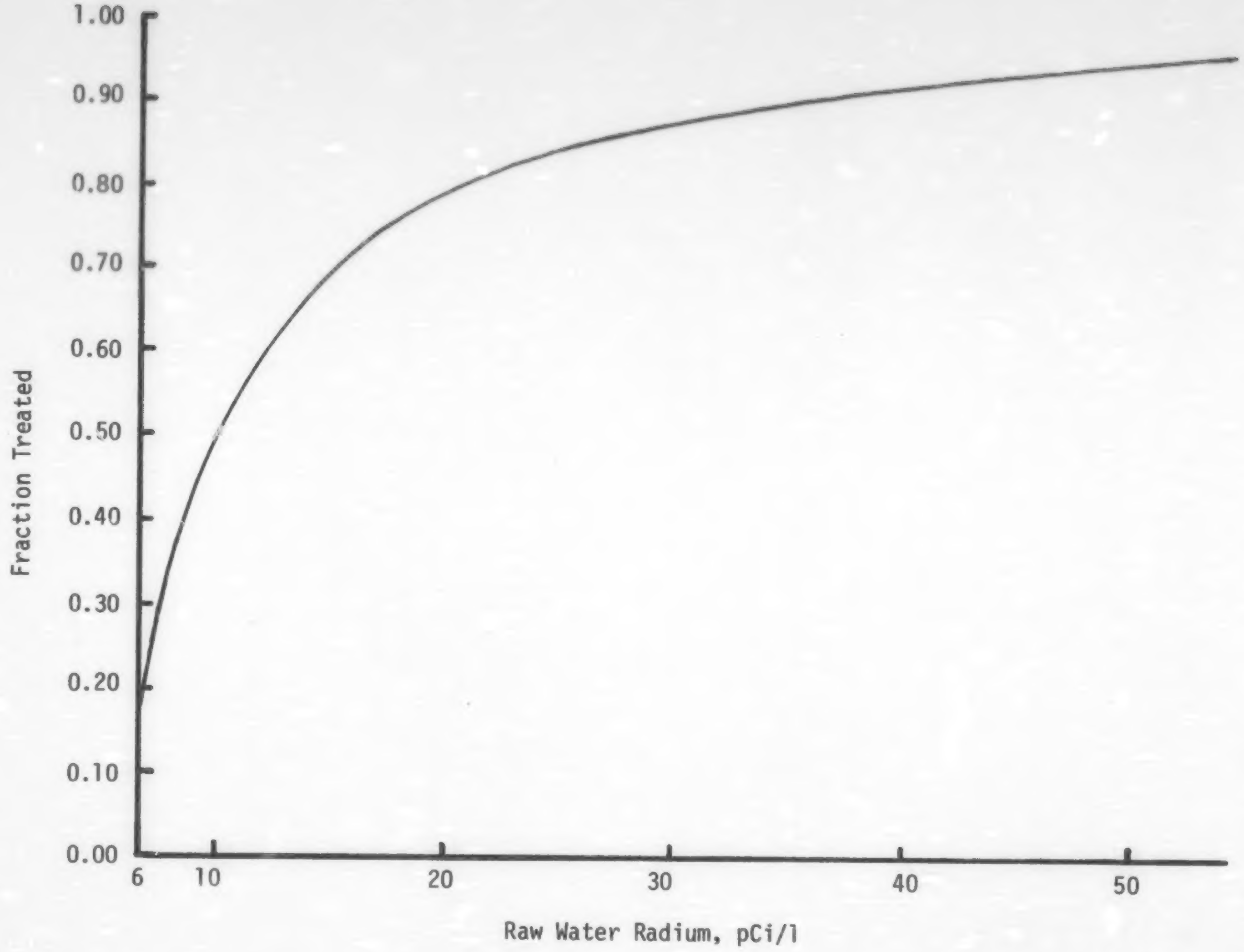


FIGURE 24. FRACTION OF WATER NEEDED TO BE TREATED AS A FUNCTION OF RAW WATER RADIUM CONCENTRATION - ION EXCHANGE

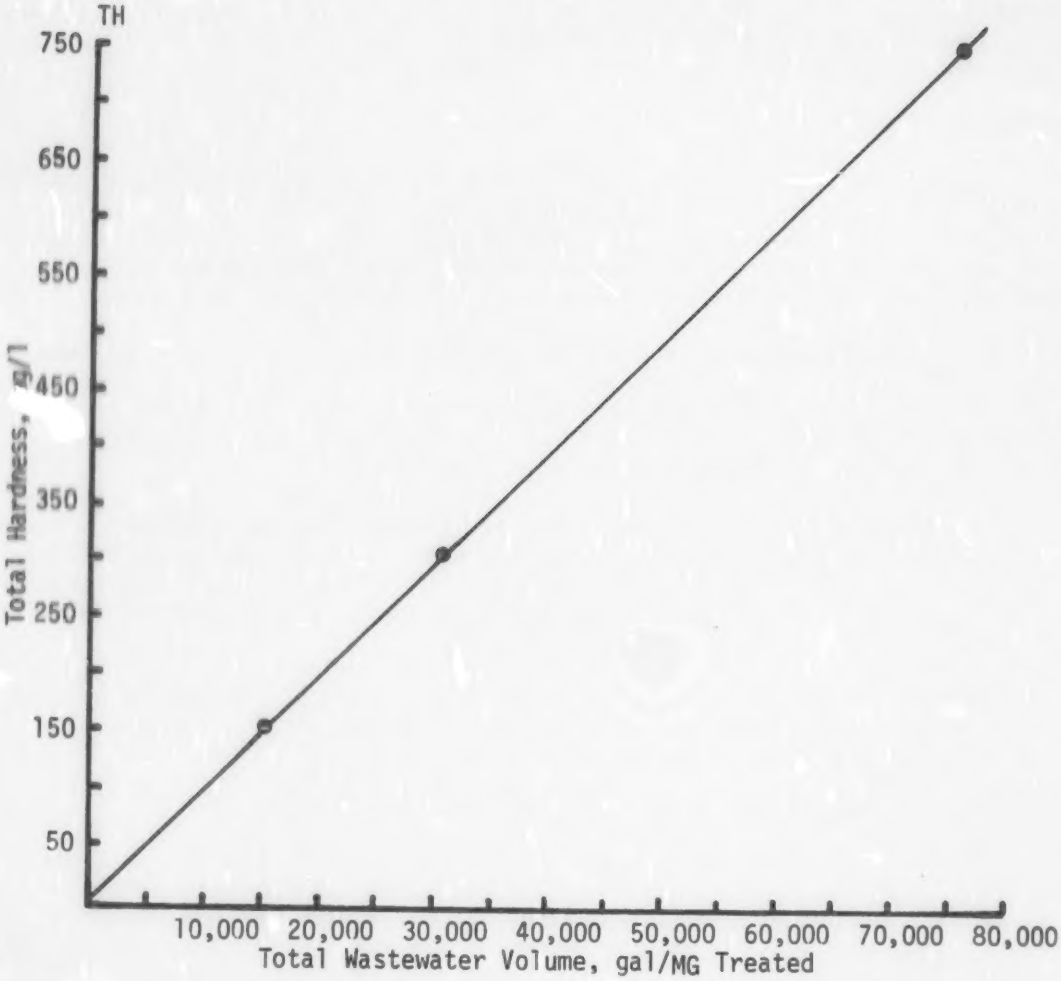


FIGURE 25. GENERATION OF WASTEWATER VOLUMES WITH ION EXCHANGE

These expressions are shown graphically in Figure 26. It is interesting to note that the radium concentration increases with decreases in the total hardness of the raw water. This is a consequence of the exchange unit being on line for a longer time at a given radium concentration when the total hardness to be removed is less. Values of the radium concentrations range from about 3000 pCi/l when the raw water radium is slightly over 50 pCi/l and the total hardness is 150 mg/l to a little over 50 pCi/l at raw water radium of 6 pCi/l and a total hardness of 750 mg/l.

BRINE DISPOSAL

One of the problems created by sodium ion-exchange softening is the disposal of spent brine from the regeneration cycle. In view of the increasing water pollution control requirements, these high salinity waters may face severe limits on discharge. This disposal problem becomes even more sensitive when the waste may contain elevated levels of radium.

The backwash water preceding the regeneration cycle may contain small amounts of iron or organic material. It is not clear whether it will also contain measurable quantities of radium when the unit is used for raw waters containing high radium concentrations. Both backwash and brine will be considered as one combined wastewater in this report.

The waste products from the brine and rinse cycle are composed principally of the chlorides of calcium and magnesium and the excess salt necessary for regeneration. The total solids in a composite sample may vary from an average concentration of 50,000 to 100,000 mg/l to a maximum of 70,000 to 200,000 mg/l.

Disposal techniques may often be limited by considerations of salinity rather than radium concentration. A list of potential alternatives for handling the wastewater streams follows:

I. Discharge
    A. To sanitary sewer
    B. To local receiving water
        1. Streams
        2. Oceans
II. Storage
    A. Evaporation lagoons
    B. Land spreading

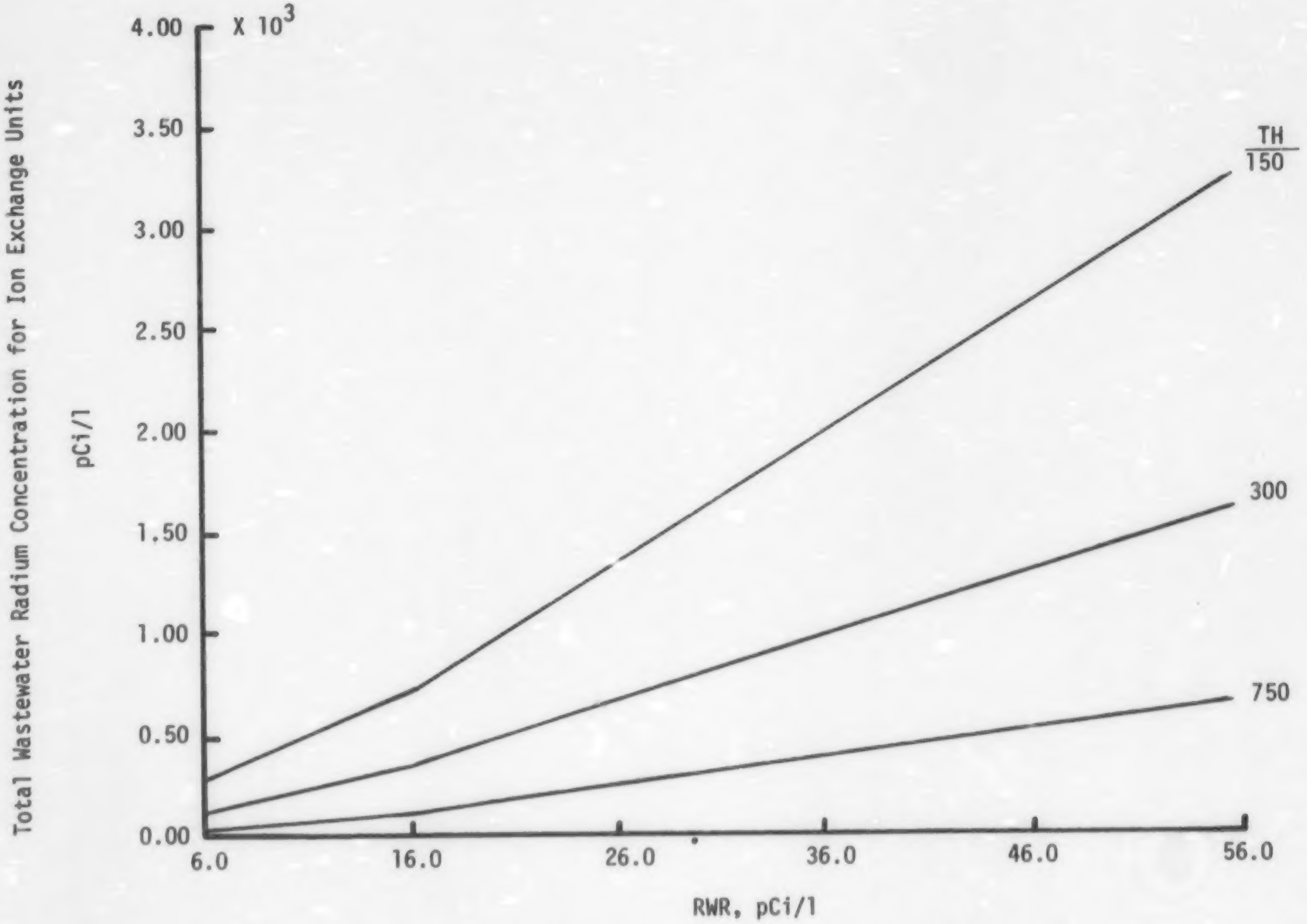


FIGURE 26. RADIUM IN ION EXCHANGE WASTE WATERS (BRINE PLUS BACKWASH)

III. Utilization - Recovery

IV. Disposal

  A. Deep aquifers

  B. Oil well fields

  C. As nuclear wastes

Discharge to Sewers

Shunting the wastewaters to sanitary sewers taxes the biological process of the waste treatment plant. In addition, much of the salinity added to the system will be eventually added to the receiving watercourse. However, there will be some dilution (100 gpcd of sewage) and some fractionation into the digested sludge. The latter phenomenon may produce a sludge that is unsuited for many of the normal uses of sewage sludge.

Discharge to Watercourse

Release of the wastewater brines from ion exchange may present a more significant problem with the salinity increase than from a radiological point of view.

If the discharge flow and the background radium concentration in the river are neglected,a simple balance shows that limited dilution is necessary:

$$\text{FLOW} = 31.6\ (\text{Pop., millions})(\text{RWR} - 5) \qquad \text{(Eq. 24)}$$

where FLOW is the river water flow in MGD necessary to dilute the effluent to a radium level of 5 pCi/l. The expression for various population ranges is graphically presented in Figure 27. Note that, even at a high radium level in the raw water and a population of 50,000, the required flow is less than 100 MGD.

If salinity and water quality standards are still incompatible, controlled dilution may be considered. Short term holding tanks or long-term lagoons will serve the purpose of allowing discharge at seasonally higher or other daily increases in streamflow. Costs, other than transportation, should be less than $0.01/1000 gallons.

Ocean outfalls are applicable to only a limited area since transportation costs rise rapidly with distance.

Evaporation Lagoons

Evaporation ponds may afford an effective method of brine disposal if the following conditions exists: (1) the net-evaporation rate (gross annual evaporation minus annual rainfall) exceeds approximately 40 in. per year;

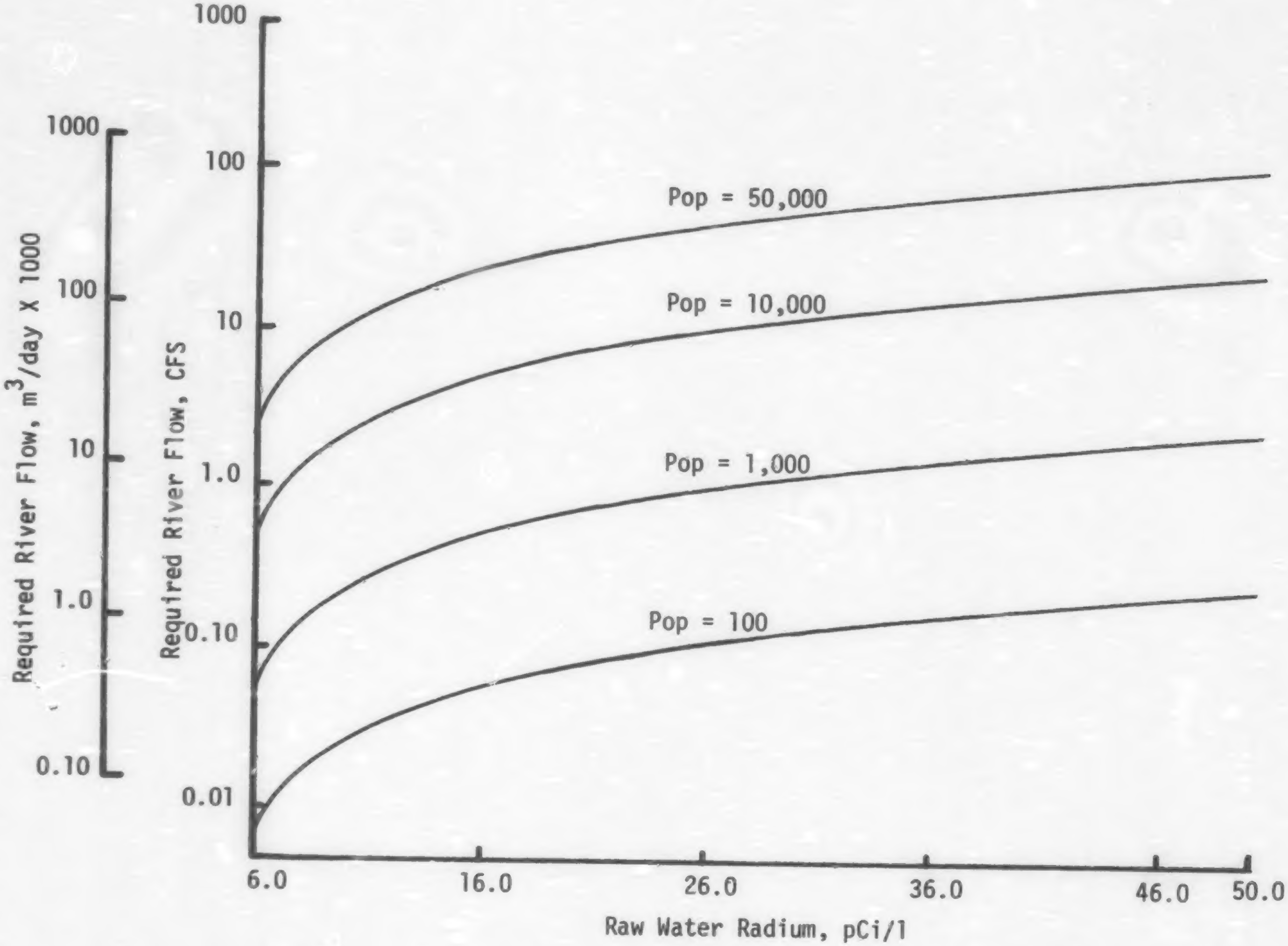


FIGURE 27. RIVER WATER FLOW REQUIRED TO DILUTE ION EXCHANGE BRINE TO 5 pCi/1.

(2) the net evaporation occurs at a uniform rate throughout the year; and (3) the impounded water is kept at shallow depths. These conditions are determined for fresh water. Since the effect of salinity increase in brine disposal ponds will reduce the rate of evaporation, disposal ponds must be designed to account for the difference in evaporation rate between fresh and saline water.

Figures 28a and 28b indicate the regional differences in rainfall and evaporation in the United States.[25] Local differences may change relative numbers considerably. Temperatures, wind movements, altitude, and topographical features all contribute to these changes.

Only lined ponds are considered for brine effluent disposal. Generally, unlined ponds permit wastes either to seep downward, contaminating usable-quality groundwater, or move laterally through the pond dike and subsequently into surface watercourses. Experience has shown that many "watertight" ponds are seepage ponds. Liner thickness should be 20-mil polyvinyl chloride (PVC) or thicker.

A dike height of 8 ft was selected by OSW[26] and is based on the following design criteria:

Assumed depth of effluent	4.0 ft
Depth to accommodate precipitate	0.5 ft
Freeboard for rainfall	0.5 ft
Freeboard for wind	2.0 ft
Soil cover over liner	1.0 ft
Total dike height	8.0 ft

The procedure covers pond sizes up to one thousand acres. In all cases, the pond is assumed to be square, as this configuration yields minimum costs.

Finally, the disposal of residual salts is an extremely difficult problem. If the pond is covered with soil, the fate of vegetation in the cover is uncertain. Transportation costs are high, even if suitable locations for disposal could be found. Some possible sites are salt mines, strip mines, and abandoned mines of other types. Radium concentration in the final salt may exceed 10^6 pCi/kg.

Landspreading

Discharge of brine wastes onto large land areas can be expected to create serious problems with cover vegetation. Although the land may serve to "absorb" large quantities of the salt before contamination of the groundwater is expected, the land may be permanently relegated for no other use. Landspreading does not appear to be a viable disposal alternative.

Recycle of Brine

Schlickelman[12] has detailed the problems in brine reclamation: "Only a portion of the partially spent brine could be used for subsequent regeneration.

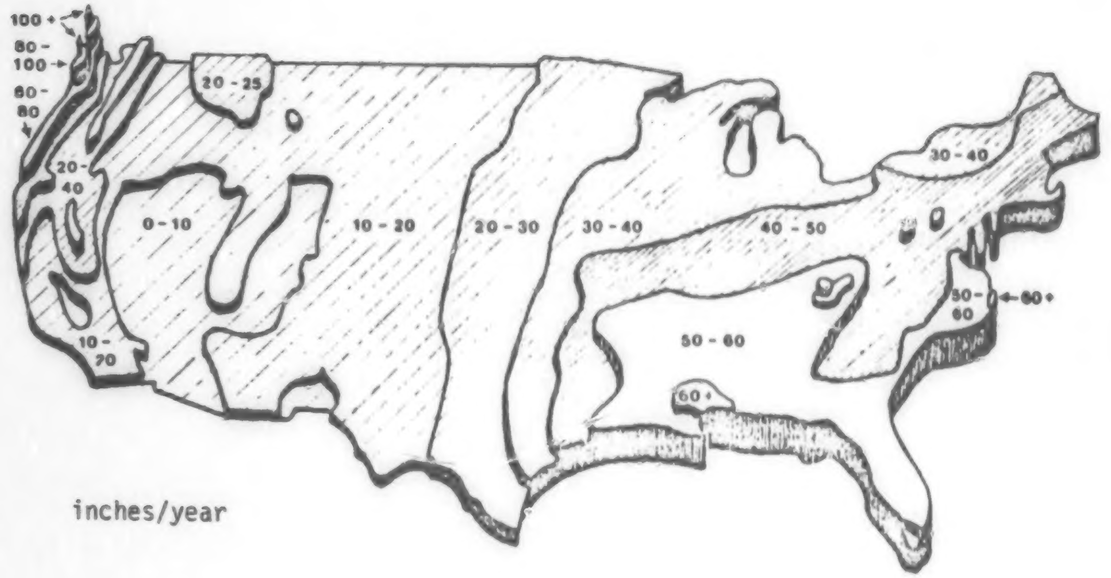


FIGURE 28a. AVERAGE RAINFALL INCLUDES ALL FORMS OF PRECIPITATION

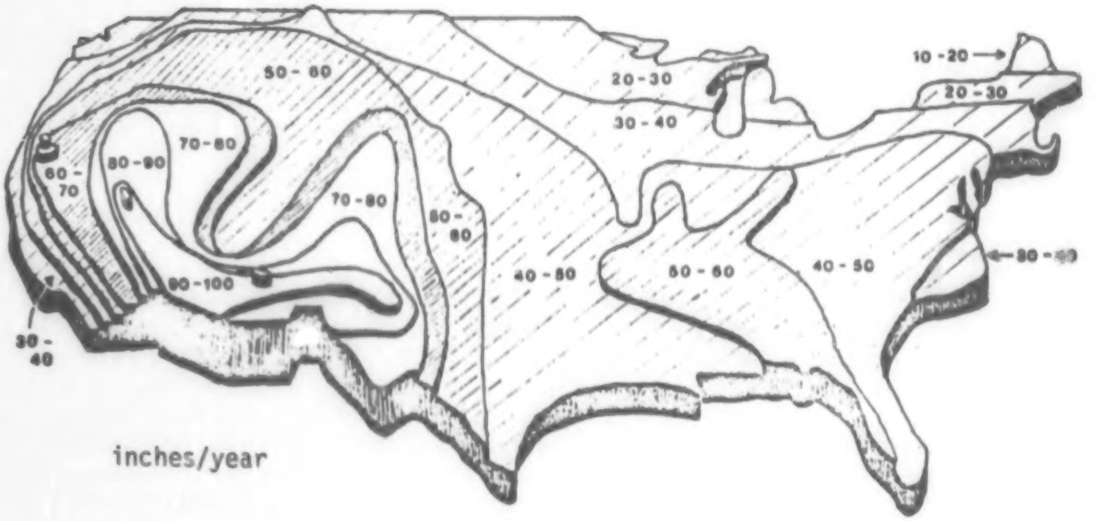


FIGURE 28b. RATE OF EVAPORATION INDICATES ABILITY TO EVAPORATE, NOT ACTUAL EVAPORATION

In general the first one-third of the spent brine from the brine rinse would contain 80 percent of the hardness. These calcium and magnesium ions interfere with the regeneration and decrease the exchange capacity. The middle one-third of brine rinse is high in sodium and might be used in subsequent regenerations to backwash the softener or used initially in the regeneration followed by sufficient fresh brine to attain the desired capacity. The principle of mass action requires an excess of salt for regeneration. Some reduced salt costs and a reduction in the amount of spent brine requiring disposal are benefits for reclamation which must be weighed against costs of additional piping and spent brine holding tanks.

Radium presents a complex problem that is not well understood. It is likely that the radium will be more tightly bound than calcium or magnesium. Therefore, the radium may be more concentrated in the middle-third of the brine. The long-term effect may be an earlier breakthrough of the radium and overall design removal may become less than 95 percent.

Brine Injection Wells

Brine wells for injection into deep aquifers may provide a means of disposing of the spent brine. It may be more feasible in the oil field well areas. Brine treatment may also be necessary for conditioning before injection into the formations. Radium levels are of no concern to the design; however, this method represents a highly desirable procedure for the radium disposal.

It must be assumed that zones or formations exist with suitable geologic characteristics for receiving the injected waste.

If an injection program is properly planned and implemented, the injected brine should remain in the receiving formation indefinitely, with little danger of pollution or destruction of other natural resources. A successful injection program requires the technical services of qualified geologists and engineers.

Very stringent criteria for disposal wells are needed to prevent pollution where subsurface injection is selected as a means of disposal. State regulations usually require that the injection well must be drilled and constructed in such a manner as to prevent brine from escaping from the disposal zone, or well, and polluting usable ground or surface waters. In part, this requires that surface casings be set through formations containing fresh groundwater and fixed permanently by circulation of cement from the bottom of the casing to the ground surface. The injection zone selected should not be one containing water of usable quality. It should have ample holding capacity for the injected waste. Casings should be set and cemented in such a manner as to ensure that the disposed brine will be confined in the injection zone. Where applicable, existing oil and gas reservoirs must be adequately protected.

The geological characteristics of a zone or formation described as suitable are:

(1) The zone must be deep enough to prevent communication of fluids between the injection zone and aquifers containing usable ground water,

(2) The fluid in the reservoir and the fluid to be injected must be compatible,

(3) The reservoir must be capable of receiving and containing the brine from the desalting plant over the life of the plant, and

(4) The zone must have sufficient porosity, permeability, thickness, areal extent, and low reservoir pressure in order to act as a storage reservoir at safe injection pressure.

As porosity, permeability, and formation thickness increase,annual disposal cost will decrease. However, as reservoir pressure and depth of the well increase, the injection cost will increase. Conversely, the opposite trend will occur in each case for decreases in these formational characteristics.

Treatment as a Nuclear Waste

If the first two-thirds of the spent brine were separated from the rinse and the final brine, then the volume to be handled would be somewhat reduced. Also, most of the radium would probably appear in this fraction. Evaporation of the general type used in nuclear plants, but without the off-gas cleanings and radiological monitoring features, could be used to obtain a sludge suitable for fixation, containment, shipment and burial. The evaporation cost may be expected to exceed $30.00/1000 gallons of brine or about $1.50 per 1000 gallons of water treated. Additional monies must be added for burial, and transportation costs will produce a third cost increment after a site is located.

COSTS OF ION EXCHANGE SOFTENING

Figures 29, 30, and 31 give the capital cost and Figures 32-34 give the annual operating costs of ion exchange softening plants for raw water radium concentrations of 7.5, 20 and 50 pCi/l, respectively.

It can be readily seen that for ion exchange, capital and annual operating costs are strongly a function of the concentrations of radium and hardness in the raw water. These costs do not include the costs of ultimate disposal of regeneration brines which will be discussed later in this report.

BRINE DISPOSAL COSTS

Several methods for brine disposal were considered for detailed calculations: lined evaporating ponds, pipeline and transmission, subsurface injection, and treatment as a nuclear waste. Assumptions and curves follow.

Costs of brine disposal by lined evaporating ponds assumed a net evaporation of five feet per year^{26} and a land costs of $1850 per acre. Capital costs included land, construction, vinyl lining, engineering design, and

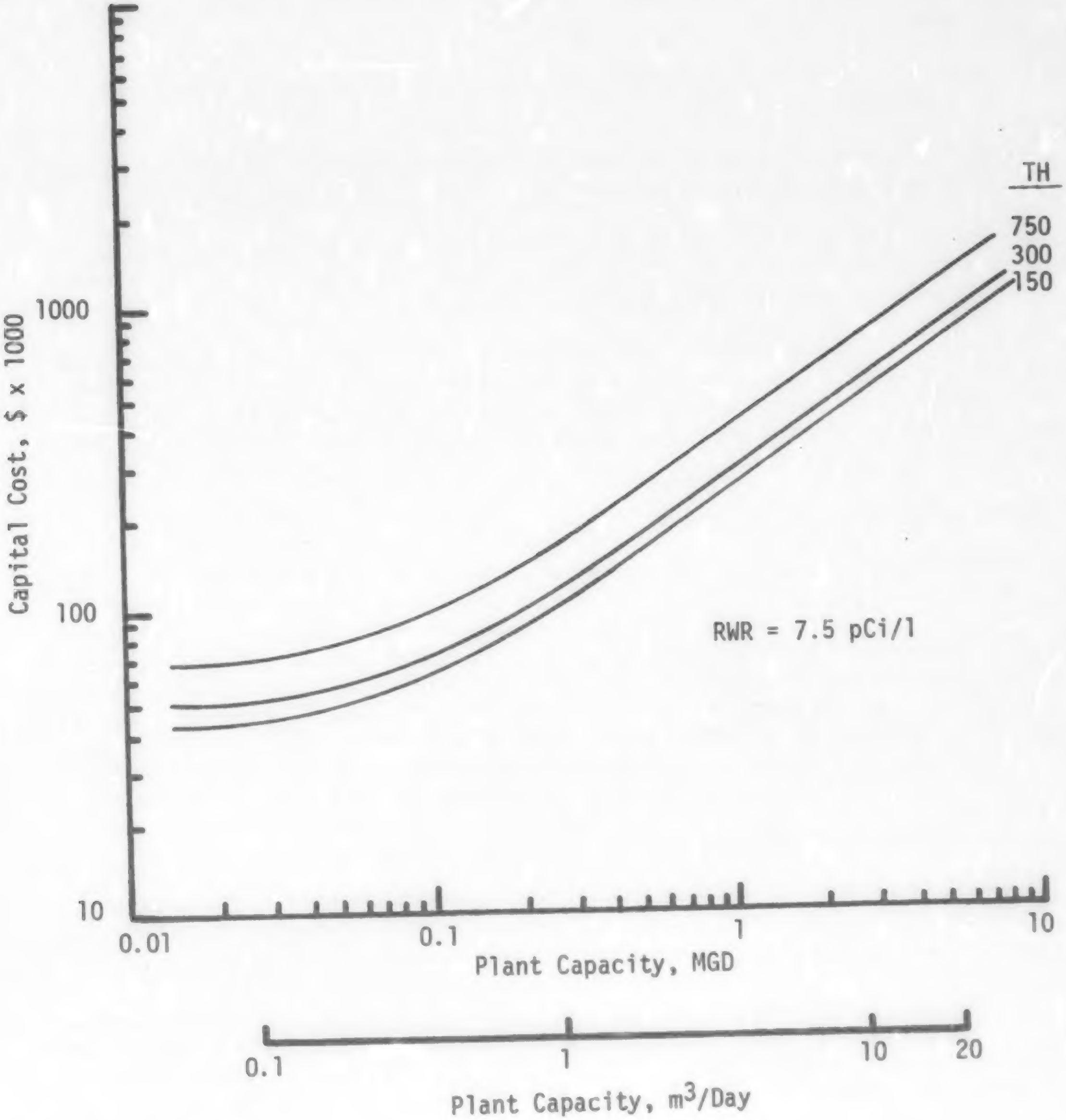


FIGURE 29. CAPITAL COSTS OF ION EXCHANGE PROCESS, RWR = 7.5 pCi/l.

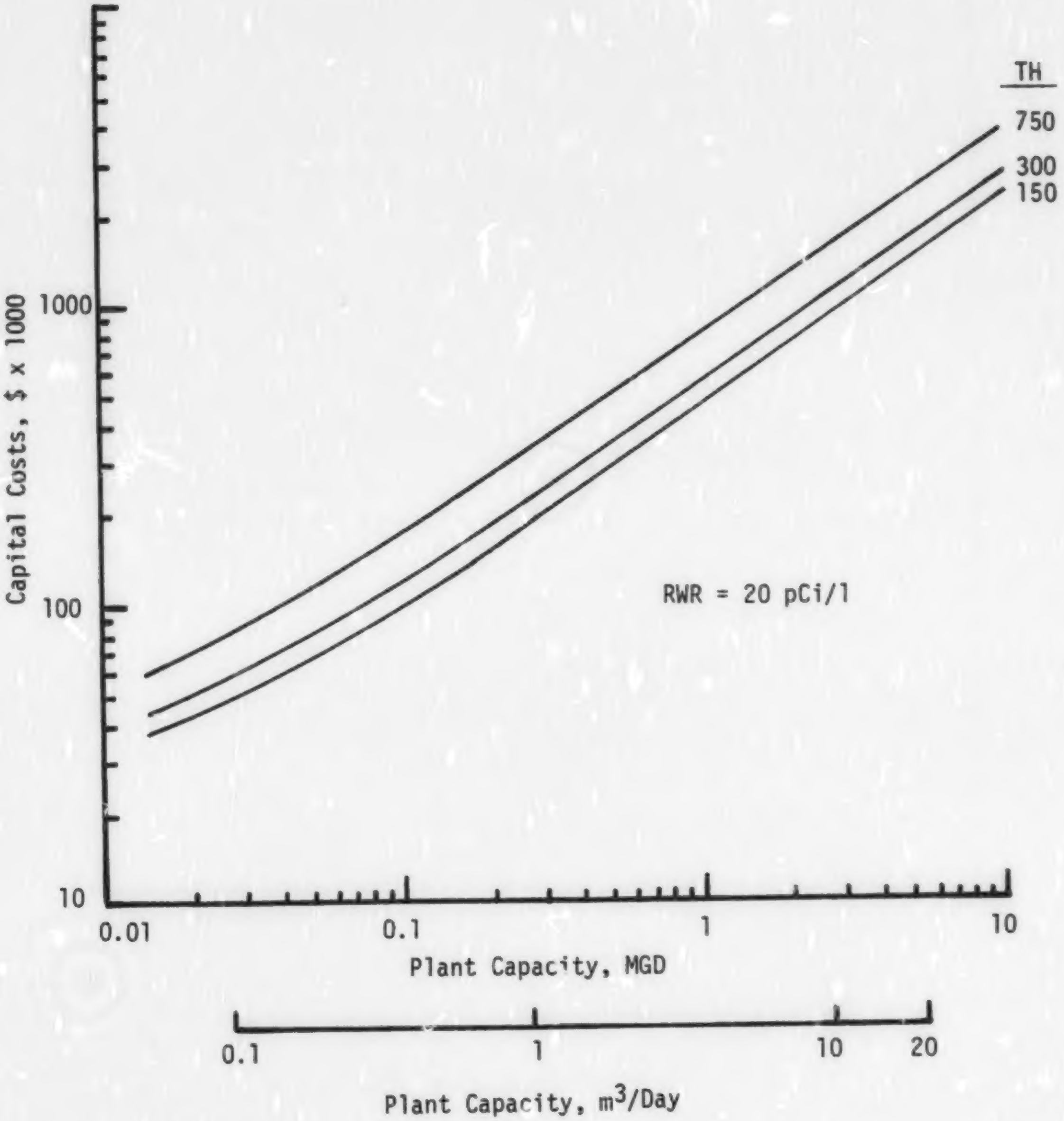


FIGURE 30. CAPITAL COSTS OF ION EXCHANGE PROCESS, RWR = 20 pCi/l

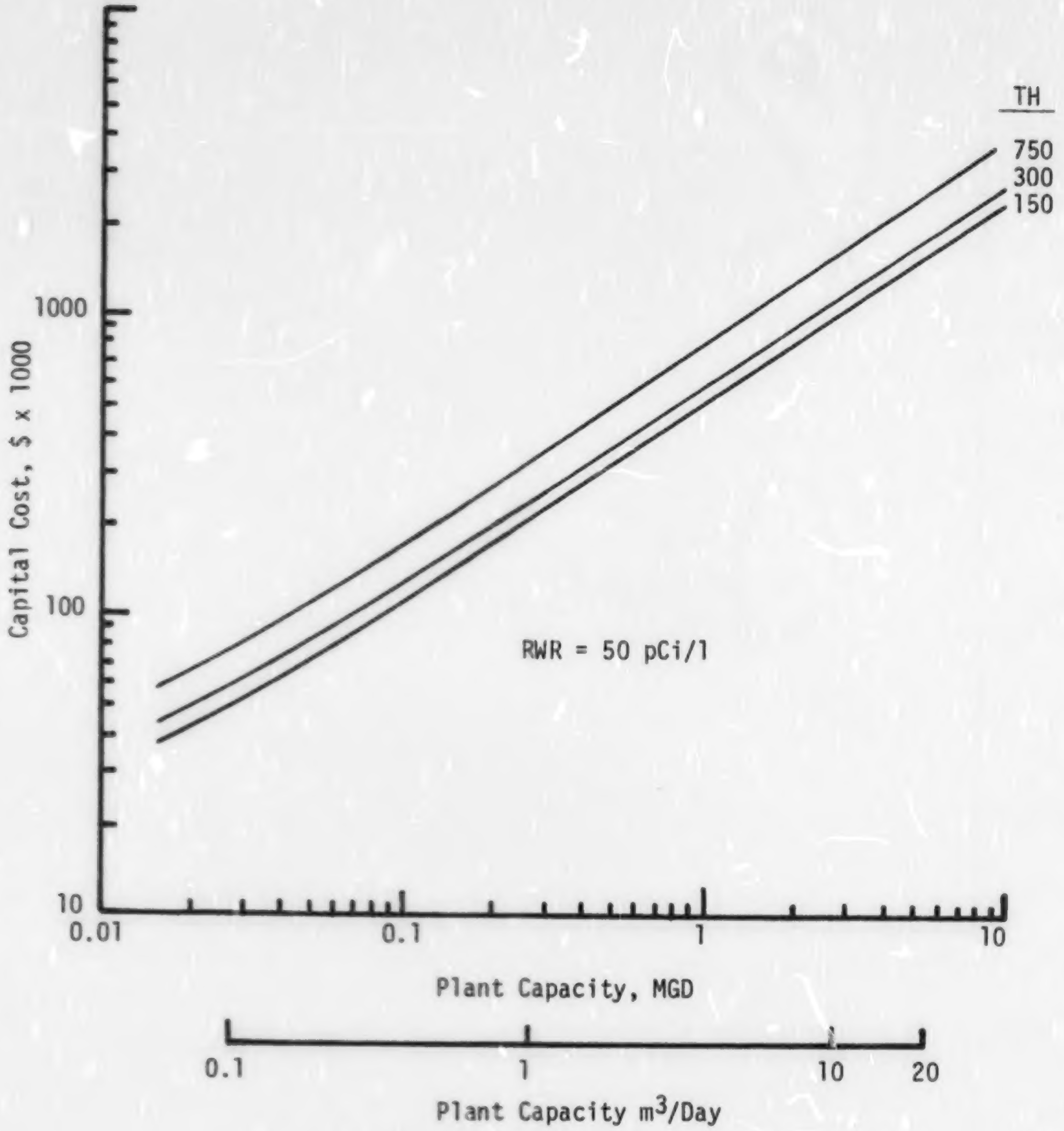


FIGURE 31. CAPITAL COSTS OF ION EXCHANGE PROCESS, RWR = 50 pCi/l.

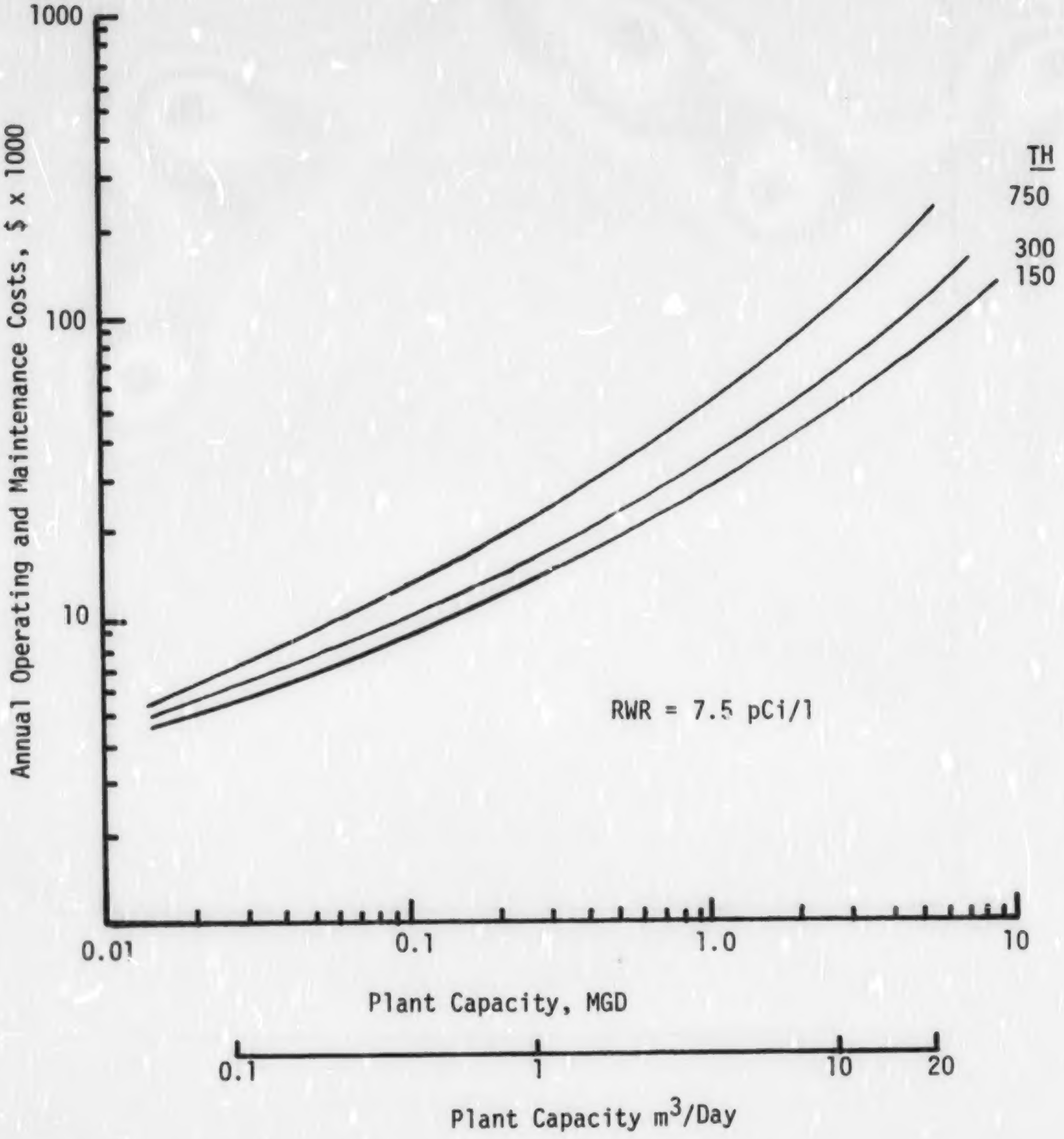


FIGURE 32. ANNUAL OPERATING AND MAINTENANCE COSTS OF ION EXCHANGE, RWR = 7.5 pCi/l.

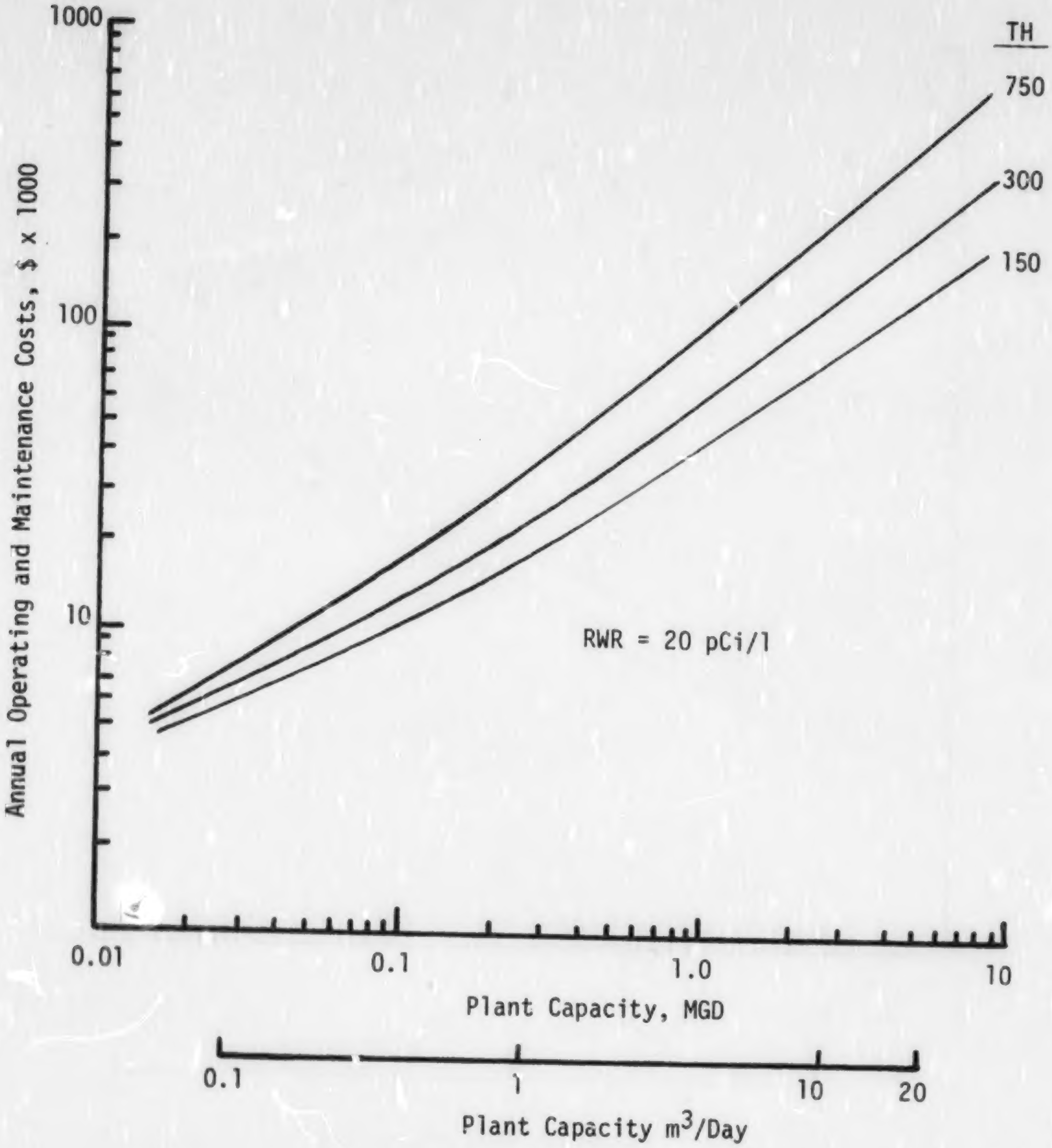


FIGURE 33. ANNUAL OPERATING AND MAINTENANCE COSTS OF ION EXCHANGE, RWR = 20 pCi/l

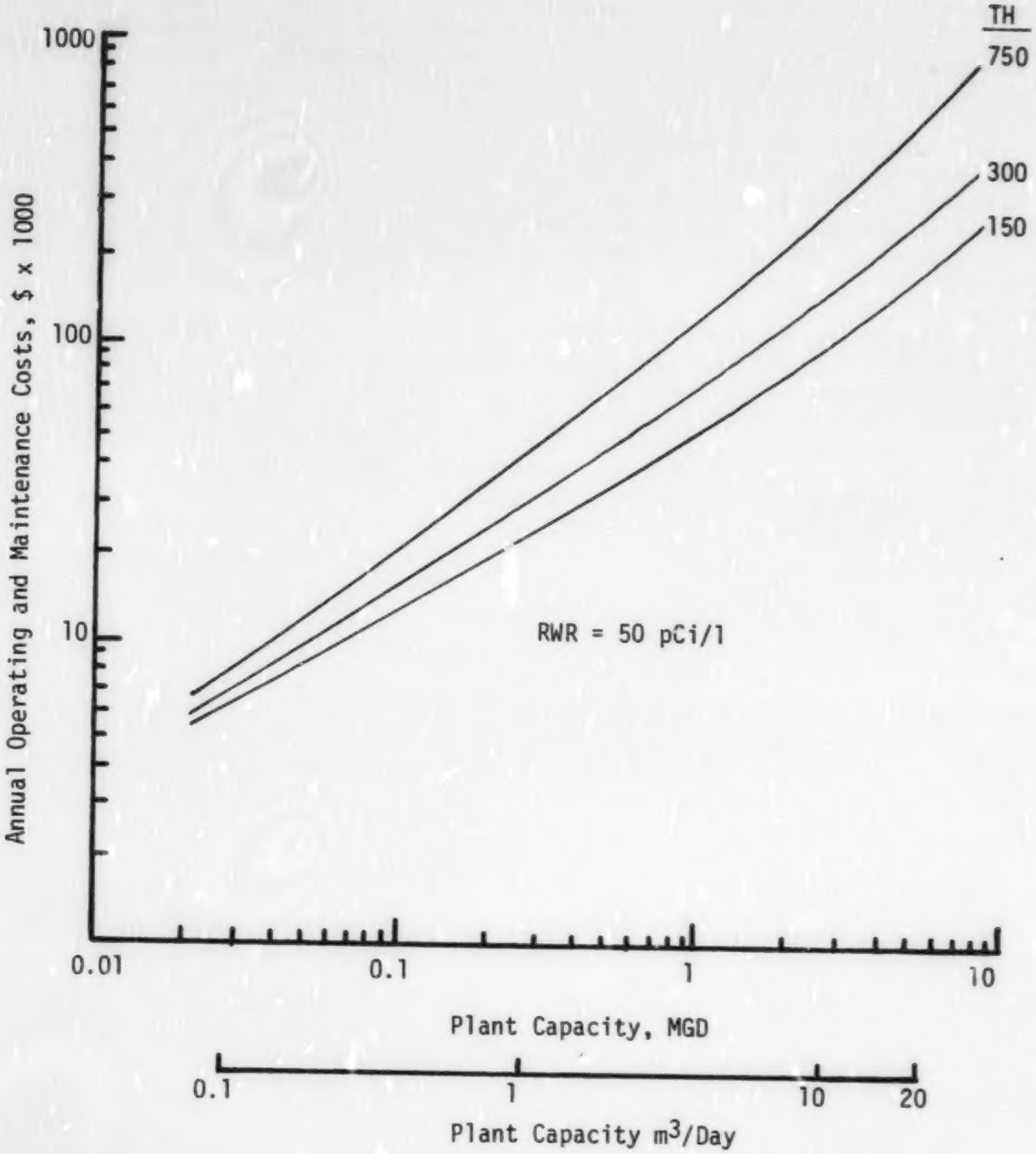


FIGURE 34. ANNUAL OPERATING AND MAINTENANCE COSTS OF ION EXCHANGE, RWR = 50 pCi/1.

contingency. Operation and maintenance costs included all labor, including payroll extras and overhead as well as supplies and repair of equipment. Figure 35 summarized the unit costs for different radium concentrations and total dissolved solids.

Costs of brine transmission to an outfall assumed one mile of pipeline and one pumping station.[26] Outfall costs were considered negligible. Capital costs included pipeline, pumping station, and right-of-way costs. Operating and maintenance costs included power labor and overhead. Figure 36 summarizes the final unit costs as a function of radium concentration and total dissolved solids.

Subsurface injection costs were calculated with basic assumptions[26] of 3000 ft depth, well-head pressure of 500 psi, an aquifer permeability of 135 millidarcies, and a porosity of 5 percent. Capital costs included wells, well-field distribution system, pumping station, storage, engineering and design, interest during construction, and contingency. Not included were environmental impact assessments required by many states. Operation and maintenance costs included power, supplies, labor and overhead. Figure 37 indicates the unit costs for different radium concentrations and total dissolved solids.

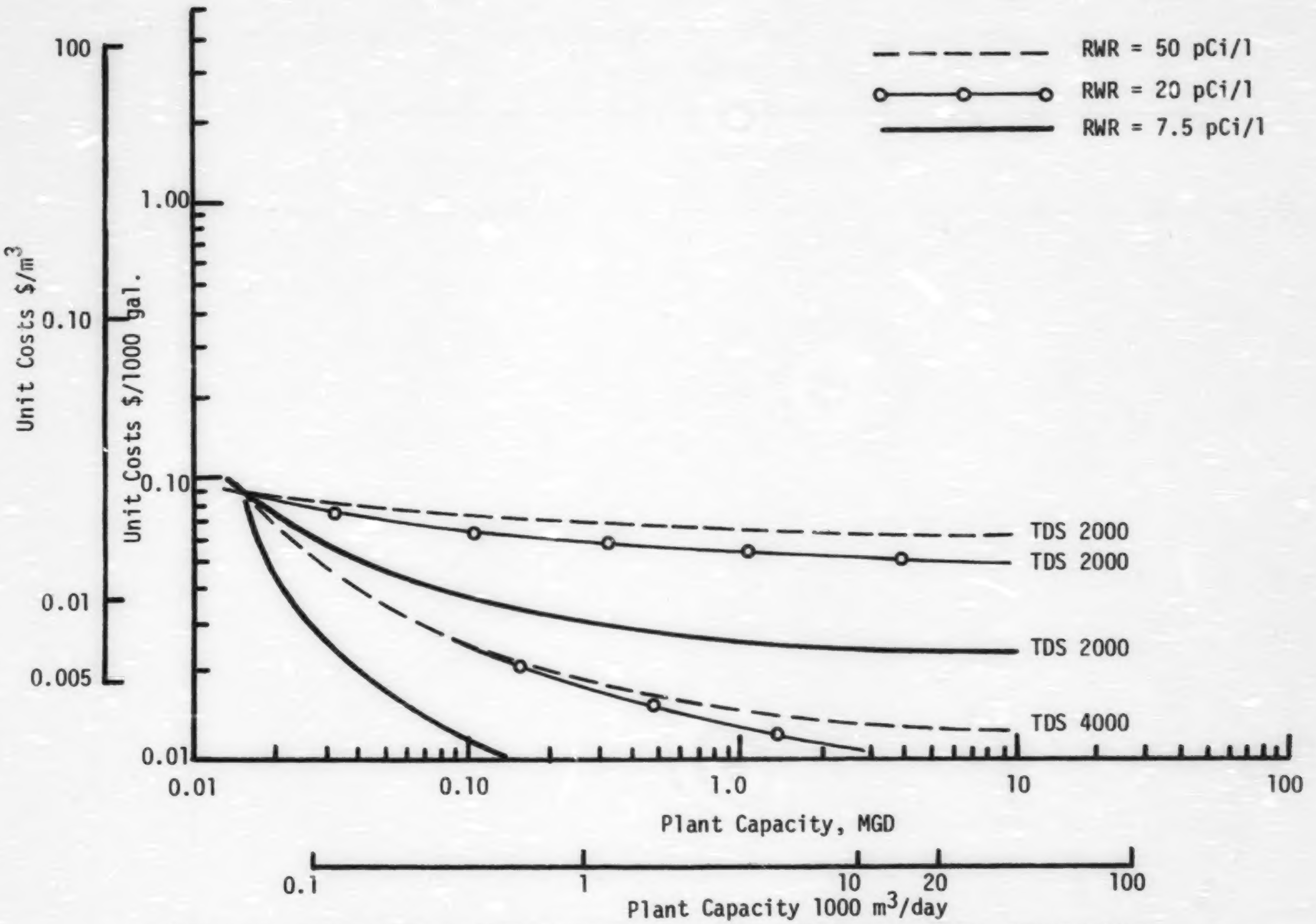


FIGURE 35. UNIT COSTS OF WASTE DISPOSAL BY LINED EVAPORATING PONDS, ION EXCHANGE.

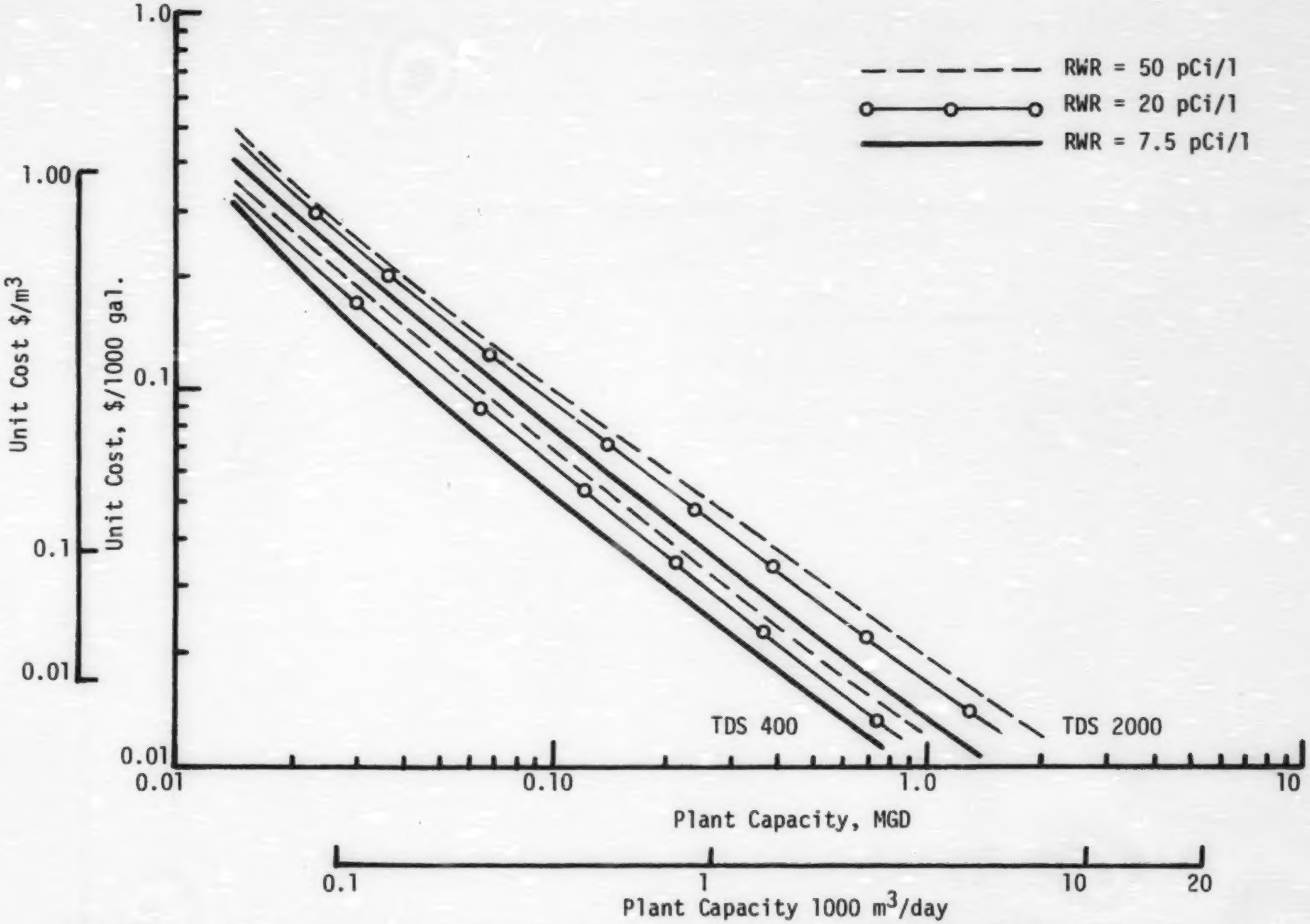


FIGURE 36. UNIT COST OF WASTE BRINE TRANSMISSION; PER MILE OF PIPELINE, ION EXCHANGE.

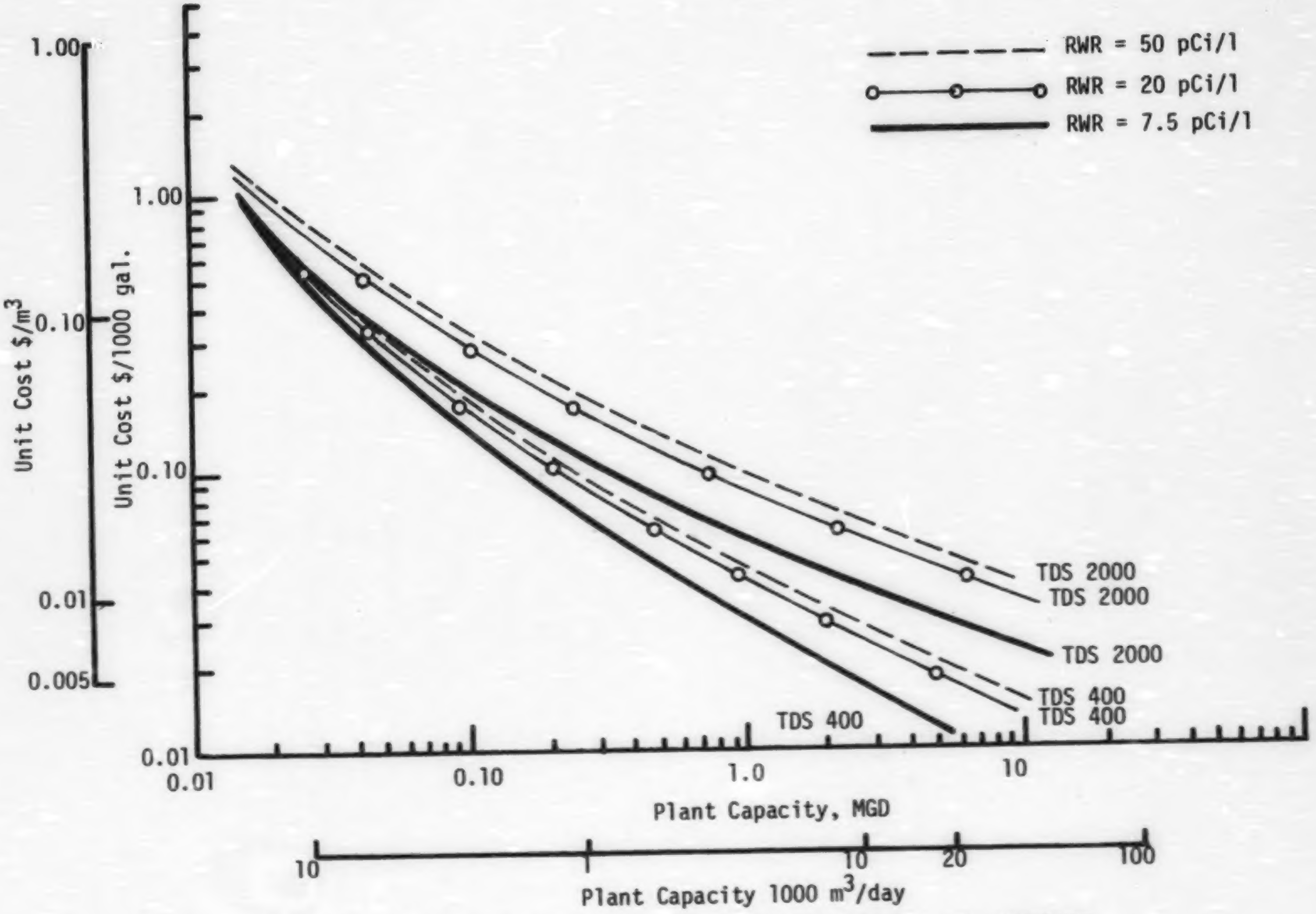


FIGURE 37. UNIT COST OF WASTE DISPOSAL BY SUBSURFACE INJECTION, ION EXCHANGE.

SECTION VIII

REVERSE OSMOSIS

GENERAL

Osmosis (Figure 38a) is the spontaneous passage of liquid from a dilute to a more concentrated solution across an ideal semipermeable membrane that allows passage of the liquid but not of dissolved solids. Obviously, reverse osmosis is a process in which the natural osmotic flow is reversed. Reversal (Figure 38b) is effected by the application of pressure to the concentrated solution sufficient to overcome the natural osmotic pressure of the less-concentrated (dilute) solution. When the amount of water passing in either direction is equal, the applied pressure can be defined as the osmotic pressure of the dilute solution having that particular concentration of solutes.

In practical applications, pumps are used to supply the pressure to overcome osmotic pressure. The water flow rate through the membrane is dependent principally upon the net driving pressure. The solute flow rate through the membrane is dependent almost solely upon the solute concentration of the feedwater.

Figure 39 illustrates a typical reverse osmosis installation. A single pressure vessel containing the membrane is shown, but there normally would be a number of pressure vessels arranged in a series-parallel array. A pump continuously feeds the pressure vessel, and the back pressure valve on the concentrate stream controls the pressure within the vessel and against the membrane. Increased pressure increases the transport rate of the permeate.[27]

Currently, there are two predominant membrane configurations: the spiral-wound module, and hollow fine fiber. The spiral-wound module (Figure 40a and 40b), was developed by Fluid Systems Division of Universal Oil Products (formerly Gulf Environmental Systems Company) in the mid-1960's, under the sponsorship of the Office of Saline Water, U.S. Department of the Interior. In this configuration, a product water collection channel is formed between two sheets of membrane by a fabric sealed in place on three of the four laminate edges. The fourth edge of the laminate is attached to a central tube, which has openings for collecting the permeate from the backing material. A mesh screen over the membrane rejection surface forms a feedwater flow channel through the module as the composite is wound around the central tube. An outer wrap is applied to maintain the modular configuration. The result is a compact package that is efficient, economical, and applicable to a wide variety of feedwaters.

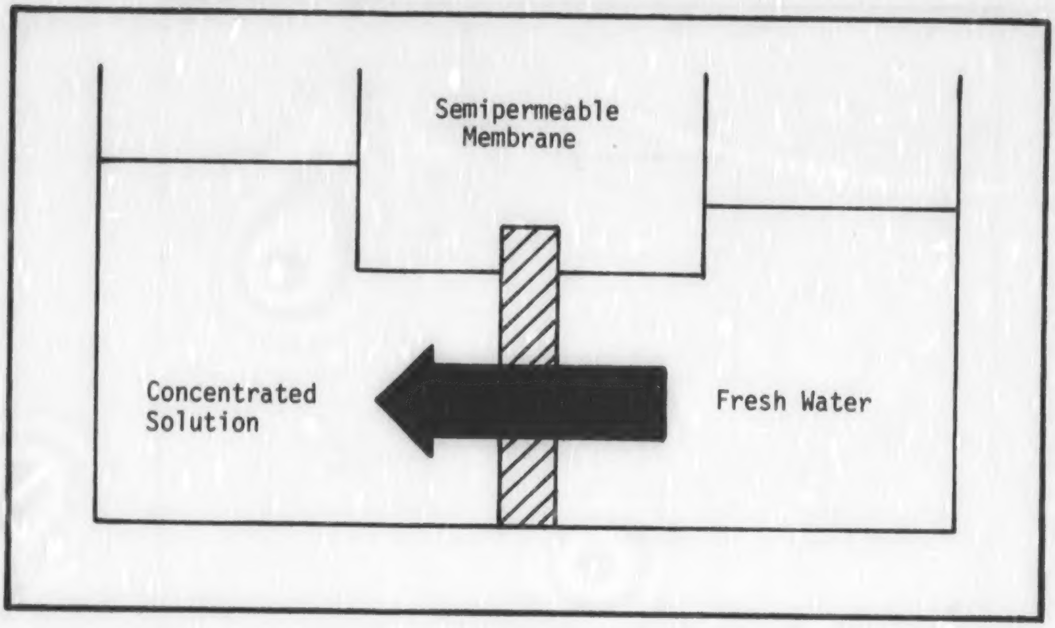


FIGURE 38a. OSMOSIS - NORMAL FLOW FROM LOW-CONCENTRATION SOLUTION TO HIGH-CONCENTRATION SOLUTION[27]

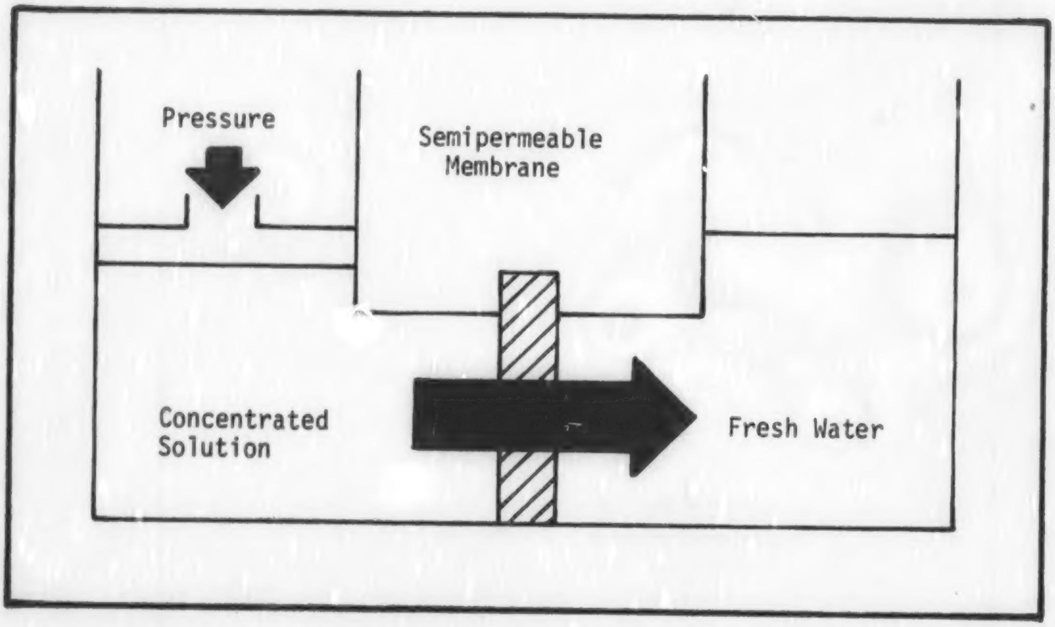


FIGURE 38b. REVERSE OSMOSIS - FLOW REVERSED BY APPLICATION OF PRESSURE TO HIGH-CONCENTRATION SOLUTION[27]

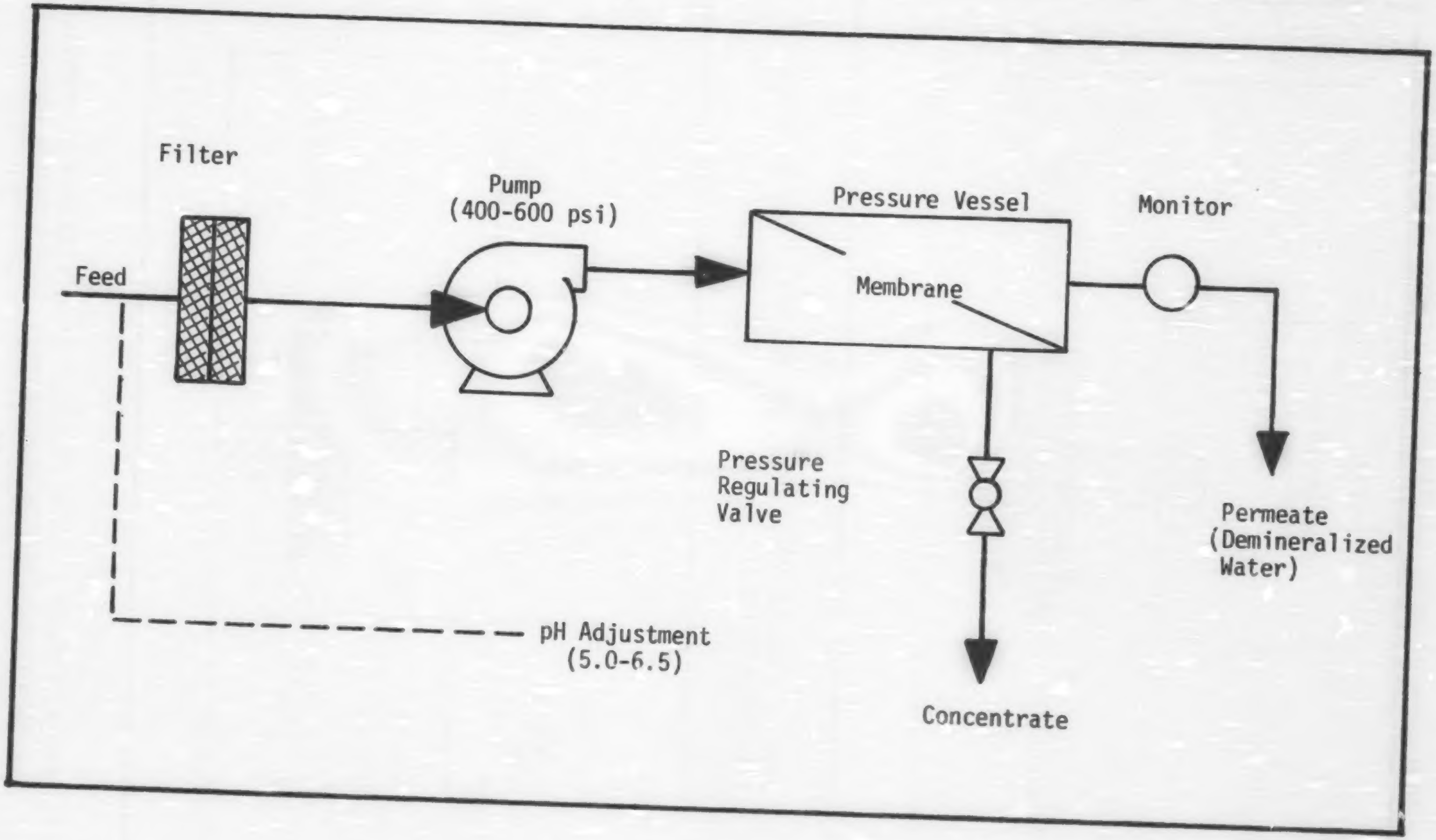


FIGURE 39. TYPICAL REVERSE OSMOSIS SYSTEM [27]

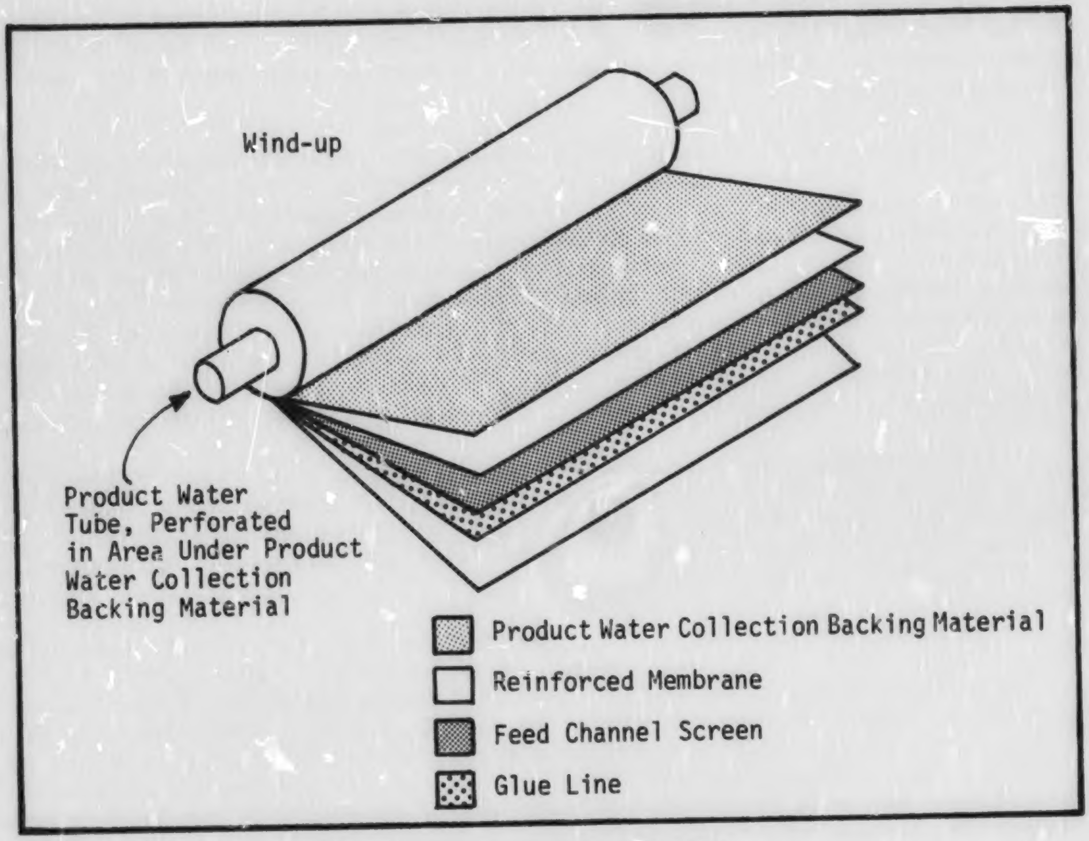

Wind-up
Product Water Tube, Perforated in Area Under Product Water Collection Backing Material
▨ Product Water Collection Backing Material
☐ Reinforced Membrane
▨ Feed Channel Screen
▨ Glue Line

FIGURE 40a. SPIRAL-WOUND MEMBRANE CONFIGURATION[27]

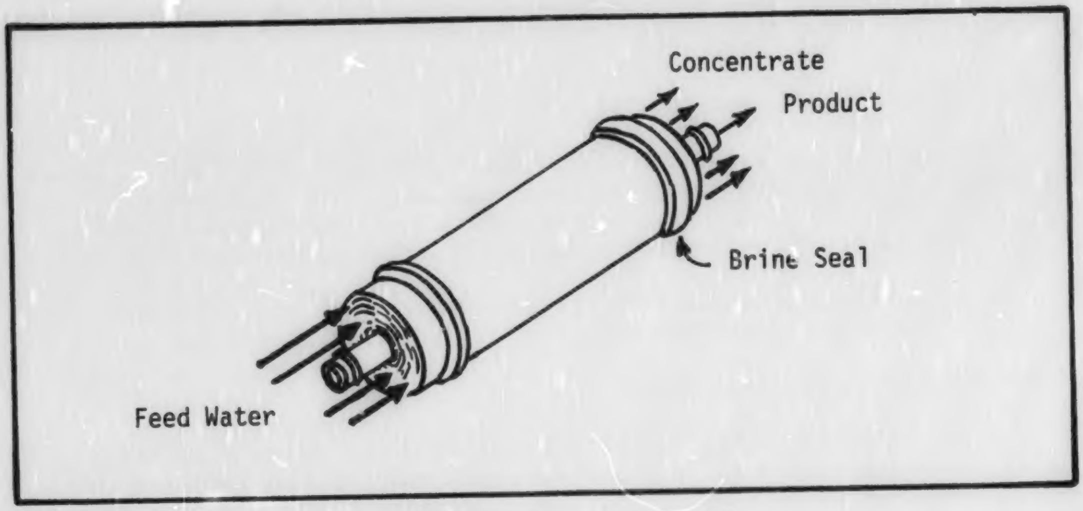


FIGURE 40b. HOLLOW FIBER MEMBRANE CONFIGURATION[27]

The hollow fine fiber configuration (Figure 40b), which uses nylon as the membrane, was developed by DuPont in the late 1960's, and later was used by Dow Chemical. DuPont now uses aromatic Polyamide membrane and Dow uses cellulose triacetate.

In the hollow fine fiber configuration, the membrane material is spun into hair-like fibers having an outer diameter of 85 to 100 microns. The fibers are bundled and potted into a header, all enclosed in a fiberglass or metal vessel. Feedwater enters the center of the vessel and is distributed radially over the bundles. Water under pressure permeates the fiber and travels inside to the permeate collection header. The wastewater continues radially over the fiber bundle and through the housing. Hollow fine fiber systems provide simplicity of installation, comparable economics to the spiral-wound system and the best packing density.[28] This membrane configuration is more susceptible to clogging, however, than the spiral-wound configuration.

The pumping pressure required to provide the driving force in the reverse osmosis process is a direct function of the concentration of dissolved solids in the feed. Reverse osmosis applications have been primarily for feedwater with TDS above a minimum of 2000 mg/l, and usually in the range of 4000-35,000 (sea water) mg/l TDS.

A characteristic of semipermeable membranes used for reverse osmosis is their greater rejection of multivalent ions such as Ca^{++}, Mg^{++}, Ra^{++}, $SO_4^{=}$, etc. than for monovalent ions Na^+, Cl^-, etc. Membranes which "soften" water by removing primarily the divalent while passing the monovalent ions are under development and may reduce the pressure requirements, and hence the cost, of softening with reverse osmosis. As of this date, no full-scale membrane softening plant is in operation and membrane softening will not be discussed further.

The primary advantage of the reverse osmosis system is its high rate of rejection of dissolved solids in the raw water. This rejection rate allows brackish and saline water to be desalted for potable use. There are several disadvantages to R/O including:

(1) high initial and operating costs

(2) need for pretreatment of raw water with turbidity removal, treatment with acid and other chemicals to prevent fouling of the membranes by slimes, suspended solids, iron, manganese, and precipitation of calcium carbonate and magnesium hydroxide.

(3) requirement to stabilize finished water with lime or other chemicals to prevent corrosion in distribution system.

RADIUM REMOVAL IN REVERSE OSMOSIS

Table 12 presents radium removal data from the two reverse osmosis plants for which radium removal data were obtained. The Greenfield, Iowa plant removed 93 percent of Ra^{226}. The difference between the two values is due to the greater passage of monovalent ions through the membrane.

Total dissolved solids removal data were not available for the Sarasota, Florida plant which also removed 96 percent of Ra^{226}. It will be assumed, for purposes of this report, that a well-operated and designed reverse osmosis unit can remove 95 percent of the influent radium activity.

TABLE 12. RADIUM REMOVAL IN REVERSE OSMOSIS PLANTS

Plant	Ra in pCi/l	Ra out pCi/l	% Ra Rem.	TDS in mg/l	TDS out mg/l	% TDS Rem.
Greenfield, IA	14.0	0.6	96	2160	164	92
Sarasota, FL	22.0	0.8	96	-	-	-

REQUIRED TREATMENT FRACTION

Figure 41 indicated the overall schematic of a reverse osmosis plant. The basic design considers a bypass fraction and a treated fraction which are reblended to achieve the required water quality. The extra raw water required for the concentrate will be neglected at this point. When both total hardness removal and radium removals are assumed to be 95 percent, the fraction of raw water to be treated in the reverse osmosis unit to achieve a finished water concentration of 5 pCi/l can be calculated as a function of raw water radium concentration and is portrayed in Figure 42. The fraction of raw water blended is one minus the fraction treated.

A mass balance to achieve a finished water at 5 pCi/l yields:

$$\text{Fraction Treated} = 1.053\ (1-(5/RWR)) \qquad \text{(Eq. 25)}$$

Design and costs calculations for the reverse osmosis unit were based on the above-mentioned premise that finished water concentration of radium would equal the limit of 5 pCi/l. It is again to be noted that many communities may desire water treated to a greater degree of hardness removed for aesthetic or health reasons. Further treatment would increase the costs above those listed in this report.

Because the waste concentrate is such a large portion of the treated flow, it cannot be considered as negligible. Figure 43 shows a schematic of the reverse osmosis process in more detail. It can be readily observed from this diagram that the raw water demands will exceed the finished water flow by the product of the fraction treated and the brine to product ratio for the unit.

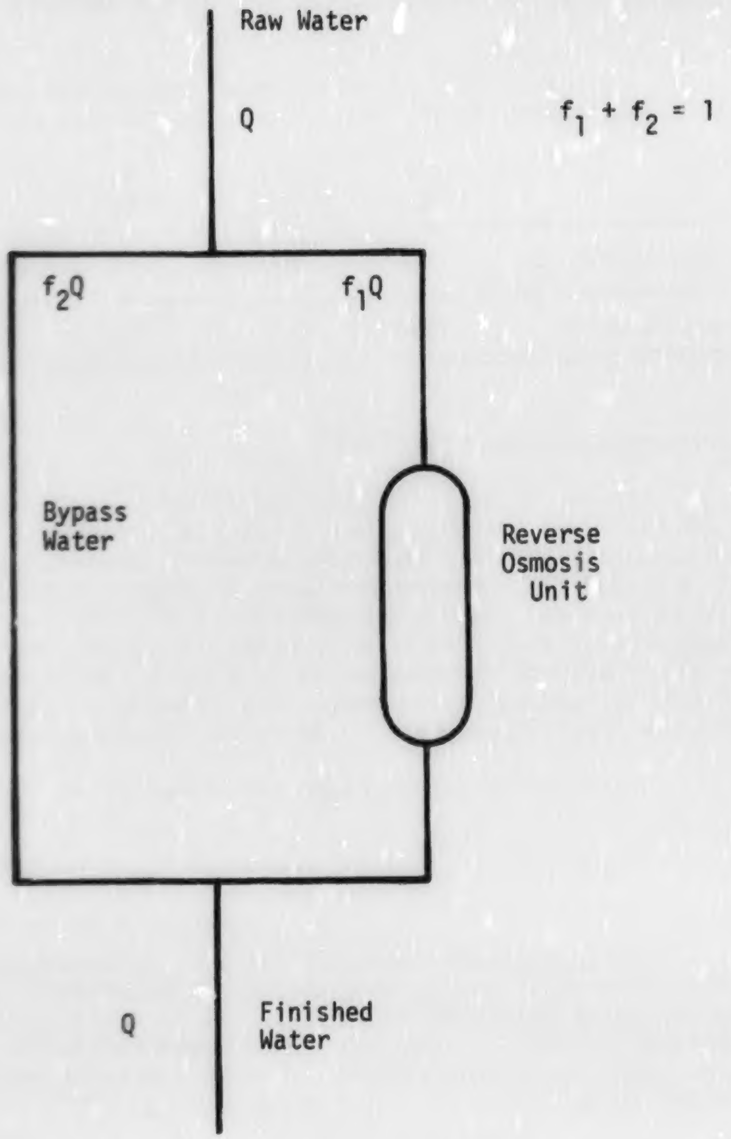


FIGURE 41. MASS BALANCE FOR DETERMINING FRACTION OF RAW WATER TO BE TREATED.

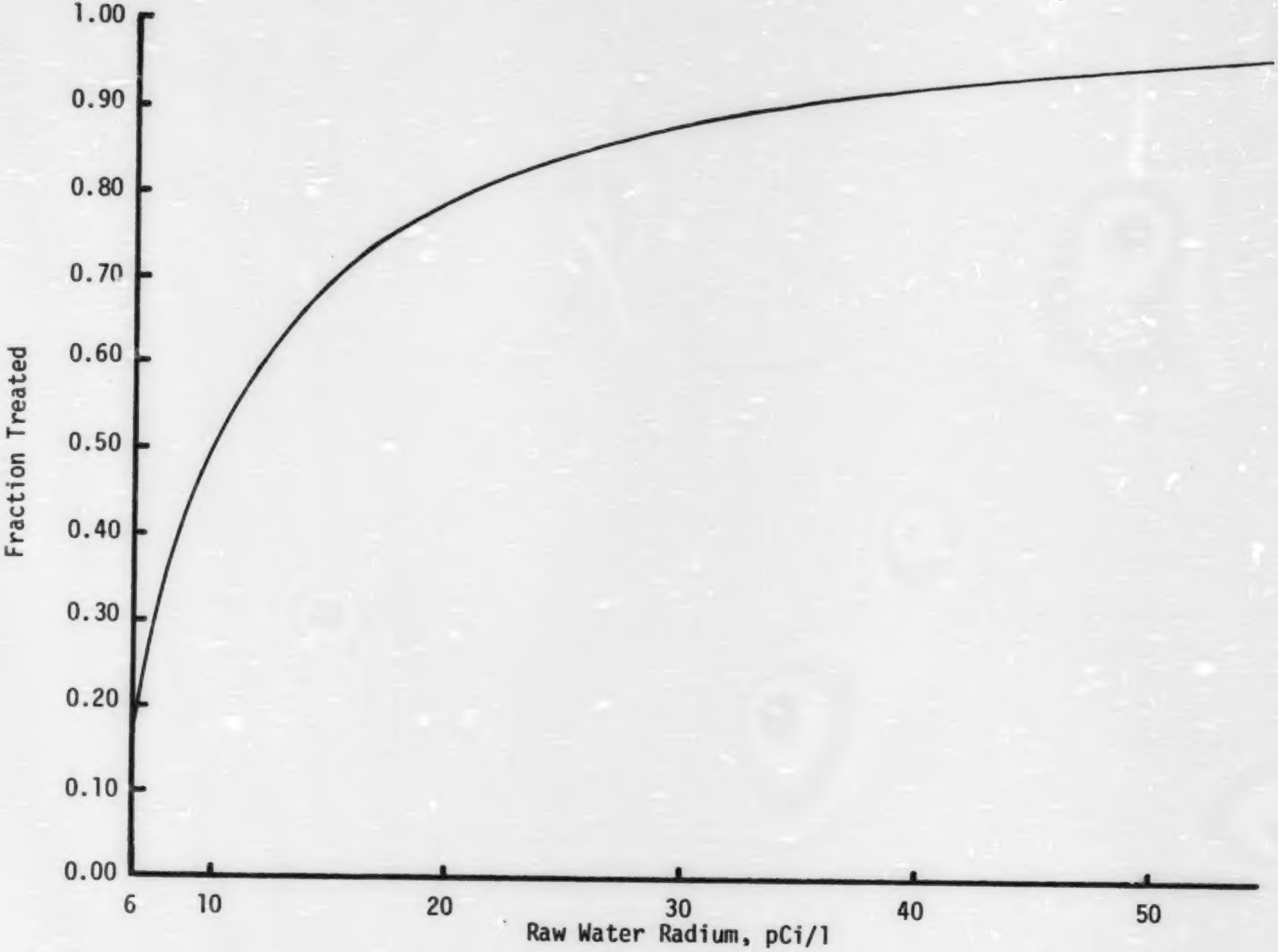


FIGURE 42. FRACTION OF WATER NEEDED TO BE TREATED AS A FUNCTION OF RAW WATER RADIUM CONCENTRATION - REVERSE OSMOSIS.

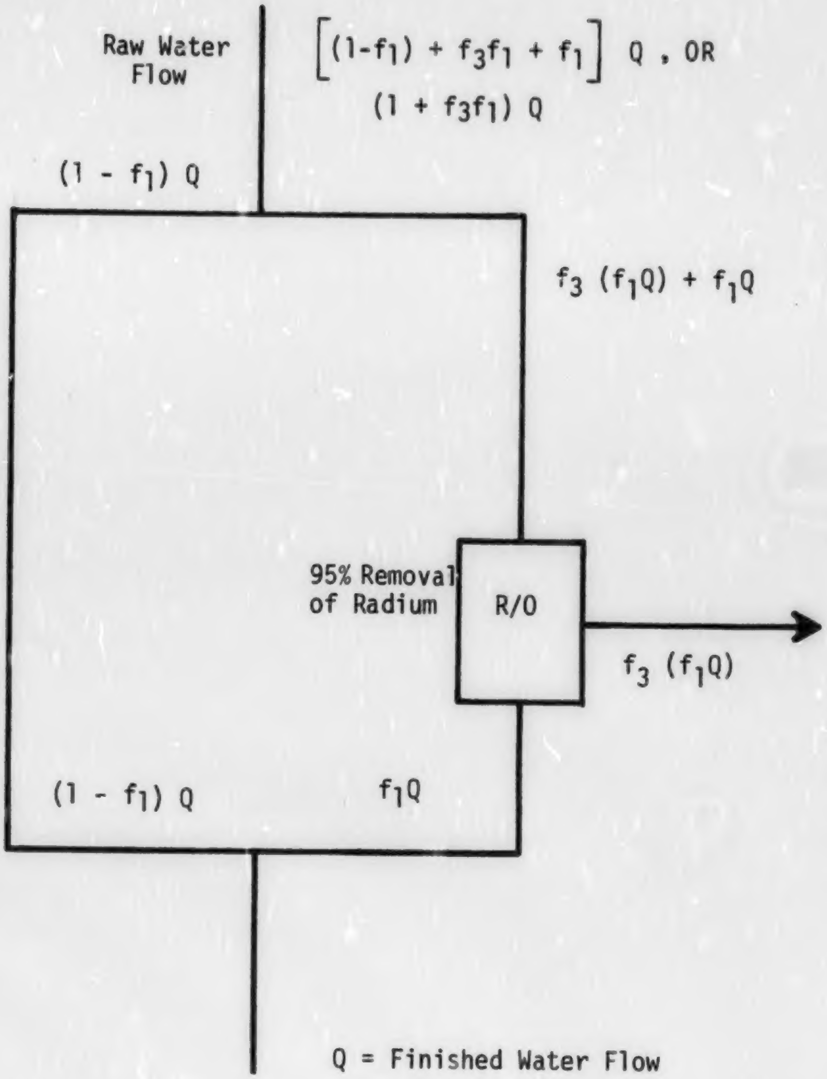


FIGURE 43. DETAILED SCHEMATIC OF REVERSE OSMOSIS PROCESS

Radium in Reverse Osmosis Brines

Table 13 indicates the calculations for predicting the brine flows in reverse osmosis. Figure 43 is used to determine the mass balances. The total brine depends upon the flow rate of finished water, the total dissolved solids concentration and the radium concentration in the raw water. However, the low and medium solids calculations are identical and the family of two curves will suffice predicting expected radium concentrations in the brines; one for less than 1500 mg/l TDS and one for greater than 1500 mg/l TDS. When the finished water radium is plotted versus the raw water radium in Figure 44 the two expressions result:

$$\text{Brine to Finished Water Ratio} \cong \frac{\text{RWR}}{48.9 + 2.84\ \text{RWR}} \qquad \text{(Eq. 26)}$$

for TDS = 2000 mg/l
and

$$\text{Brine to Finished Water Ratio} \cong \frac{\text{RWR}}{120.5 + 6.99\ \text{RWR}} \qquad \text{(Eq. 27)}$$

for TDS = 1000 mg/l or less.

Radium contents in the waste brine can be determined with the following expression:

$$\text{Brine Radium Concentration, pCi/l} = \text{RWR}\left[1 + 0.95\ \frac{\text{fraction treated}}{\text{brine to product ratio}}\right] \qquad \text{(Eq. 28)}$$

When Equations 26 and 27 are substituted into Equation 28 the radium concentration in the brine becomes a function only of the raw water radium concentration:

$$\text{Brine Radium Concentration, pCi/l} = \text{RWR}\left[1 - 0.95\ \frac{1.053(1 - 5/\text{RWR})}{\dfrac{\text{RWR}}{a + b\ \text{RWR}}}\right] \qquad \text{(Eq. 29)}$$

when $a = 48.9$, $b = 2.84$ for TDS = 2000 mg/l
and $a = 120.5$, $b = 6.99$ for TDS $\leq$ 1000 mg/l
These expressions are plotted in Figure 45.

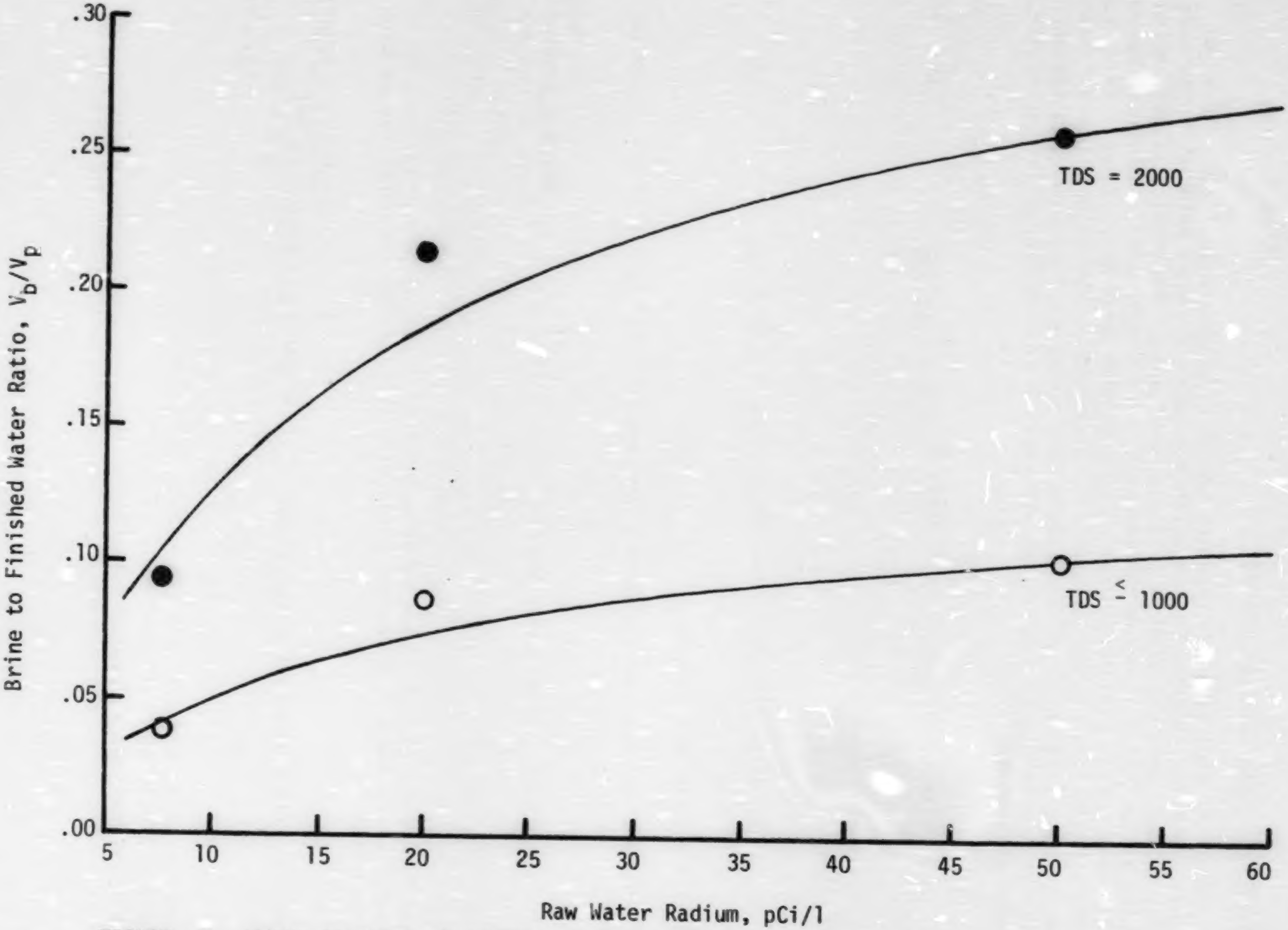


FIGURE 44. BRINE TO FINISHED WATER, REVERSE OSMOSIS.

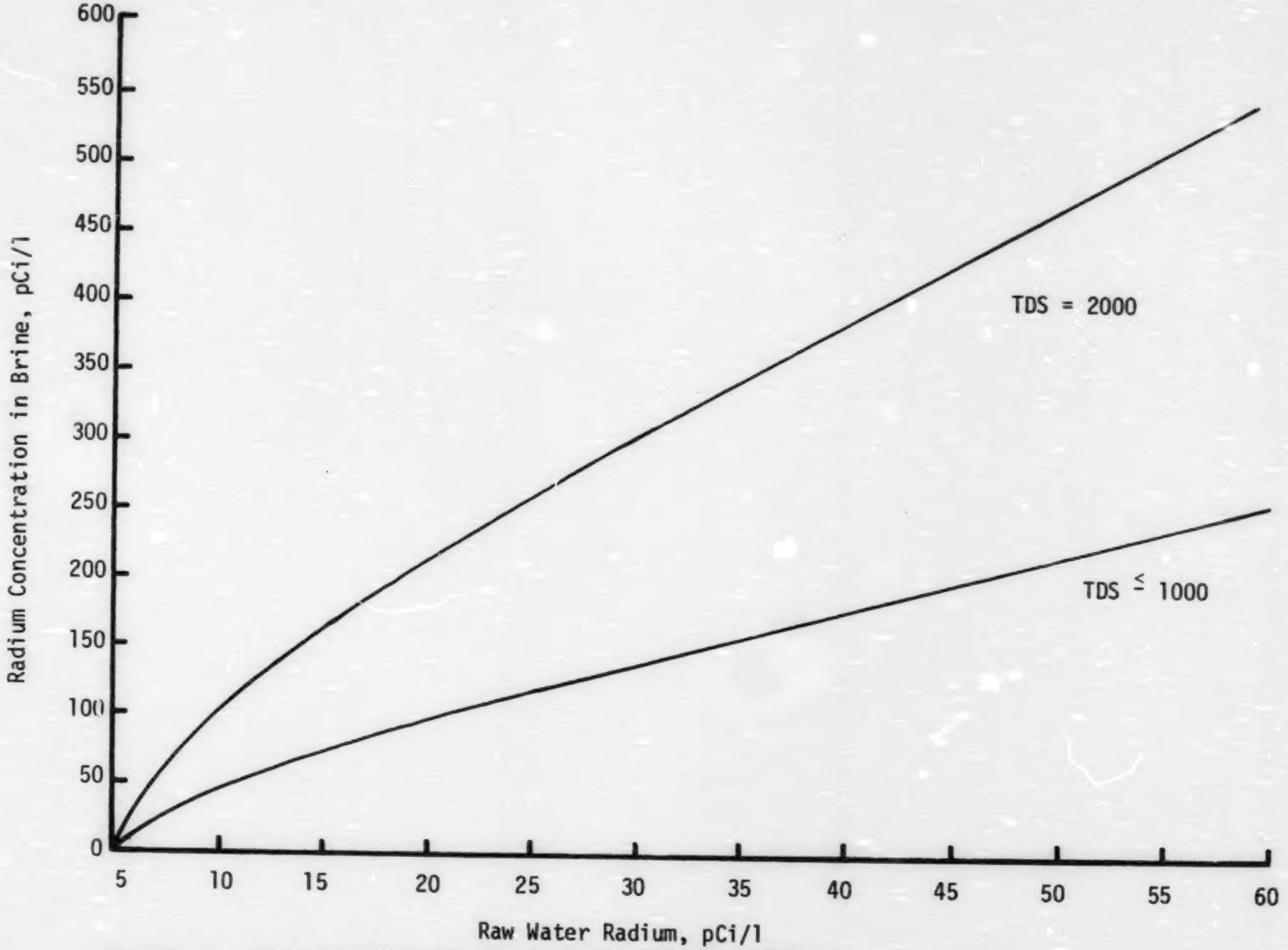


FIGURE 45. RADIUM CONCENTRATION IN BRINE, REVERSE OSMOSIS.

TABLE 13. BRINE VOLUMES IN REVERSE OSMOSIS

Total Dissolved Solids mg/l	Raw Water Radium pCi/l	Treated Fraction f_1	Brine to Product Ratio	Brine to Finished Water Ratio	Raw to Finished Water Ratio
2000	7.5	0.351	0.271	0.0951	1.0951
2000	20	0.789	0.271	0.214	1.214
2000	50	0.947	0.271	0.257	1.257
1000	7.5	0.351	0.110	0.0386	1.0386
1000	20	0.789	0.110	0.0868	1.0868
1000	50	0.947	0.110	0.1042	1.1042
400	7.4	0.351	0.110	0.386	1.0386
400	20	0.789	0.110	0.0868	1.0868
400	50	0.947	0.110	0.1042	1.1042

BRINE DISPOSAL

Problems in disposal of brines from a reverse osmosis plant are similar to those discussed previously for an ion exchange plant. However, for every unit of hardness removed more water is required by the reverse osmosis plant and therefore the concentration of salt is less than for an ion exchange plant and the volume is much greater. The water pollution control requirement may be somewhat lessened due to these characteristics, but the wastewater containing elevated levels of radium may face the same public sensitivity.

The flow of wastewater from a reverse osmosis plant is more constant with time. The reject stream may contain about three times the total solids in the original feed.

Disposal techniques may often be limited by considerations of salinity rather than radium concentration. The list of potential alternatives for handling the wastewater streams is similar to ion exchange except that utilization of the brine is not feasible. Possible alternatives are:

I. Discharge

  A. To sanitary sewer

  B. To local receiving water

II. Storage

  A. Evaporation lagoons

  B. Land spreading

III. Disposal

   A. Deep aquifers

   B. Oil well fields

   C. As nuclear wastes

Discharge to Sewers

Shunting the wastewaters to sanitary sewers taxes the biological process of the waste treatment plant. In addition, the volume of wastewater to be handled is more significant than for ion exchange plants and the salinity added to the system will be eventually added to the receiving watercourse. However, there will be some dilution (100 gpcd of sewage) and some fractionation into the digested sludge. The latter phenomenon may produce a sludge that is unsuited for many of the normal uses of sewage sludge.

Discharge to Watercourse

Release of the wastewater brines from reverse osmosis plants may present more significant problems from salinity than from a radiological consideration. The following discussion concentrates on the radioactivity aspects.

If the background radium concentration in rivers is neglected, a simple balance shows that limited dilution is necessary:

$$\text{FLOW} \approx [(\text{Pop., millions})(113)(\text{RWR})^2]/(a + b\ \text{RWR}) \qquad \text{(Eq. 30)}$$

where FLOW is the river water flow in MGD necessary to dilute the effluent to a radium level of 5 pCi/l. The expression for various population ranges is graphically presented in Figure 46. Note that, even at a high radium level in the raw water and a population of 50,000, the required flow is less than 100 MGD.

If salinity and water quality standards are still incompatible, controlled dilution may be considered. Holding lagoons will serve the purpose of allowing discharge at seasonally higher or other daily increases in streamflow. Costs, other than transportation, should be less than $0.02/1000 gallons.

Ocean outfalls are applicable to only a limited area since transportation costs rise rapidly with distance.

Evaporation Lagoons

Evaporation ponds may afford an effective method of brine disposal if the following conditions exist: (1) the net evaporation rate (gross annual evaporation minus annual rainfall) exceeds approximately 40 in. per year; (2) the net evaporation occurs at a uniform rate throughout the year; and (3) the

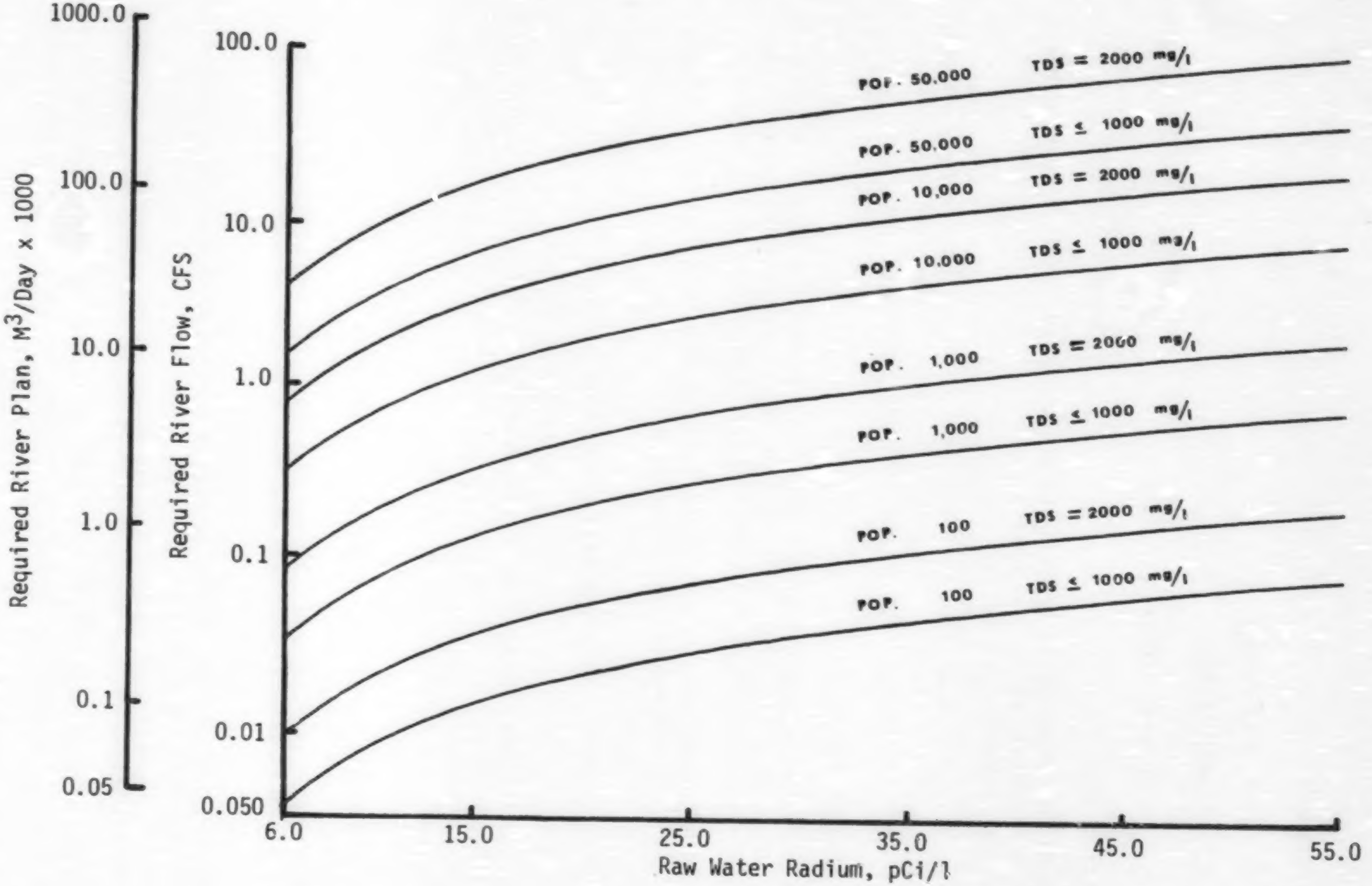


FIGURE 46. RIVER WATER FLOW REQUIRED TO DILUTE REVERSE OSMOSIS BRINE TO 5.0 pCi/l

impounded water is kept at shallow depths. These conditions are determined for fresh water. Since the effect of salinity increase in brine disposal ponds will reduce the rate of evaporation, disposal ponds must be designed to account for the difference in evaporation rate between fresh and saline water.

Acreage required for reverse osmosis plants will greatly exceed those needed for ion exchange plants. Additional discussion of lagoon features is found under the ion exchange section.

Landspreading

Discharge of reverse osmosis brine wastes onto large land areas can be expected to create serious problems with cover vegetation. Although the land may serve to "absorb" large quantities of the salt before contamination of the ground water is expected, the land may be permanently relegated for no other use. Landspreading does not appear to be a viable disposal alternative.

Brine Injection Wells

Brine wells for injection into deep aquifers may provide a means of disposing of the spent brine. The volumes to be handled greatly exceed those in the ion exchange brine problem. The lower salinity may negate the necessity for conditioning before injection into the formations. Radium levels are of no concern to the design however, this method represents a highly desirable procedure for the radium disposal. More sites may be suitable at the lower salinity. More detailed discussions of subsurface injection has been given in the ion exchange section.

Treatment as a Nuclear Waste

Evaporators of the general type used in nuclear plants, but without the offgas clearings and radiological monitoring features could be used to obtain a sludge suitable for fixation, containment, shipment and burial. The evaporation cost may be expected to exceed $30.00/1000 gallons of brine or about $6.00/1000 gallons of water treated.

COST OF REVERSE OSMOSIS SOFTENING

Figure 47 presents the capital cost of reverse osmosis systems designed to reduce radium in the finished water to the limit of 5.0 pCi/1. Figure 48 presents the annual operating and maintenance costs for reverse osmosis treatment. Both cost curves are shown as a function of raw water radium and plant capacity only.

The range of raw water TDS investigated in this report is 400 - 2000 mg/1, and very little cost data is available for reverse osmosis treatment of low solids raw water. The costs presented are for low brackish waters <4000 mg/1 TDS.

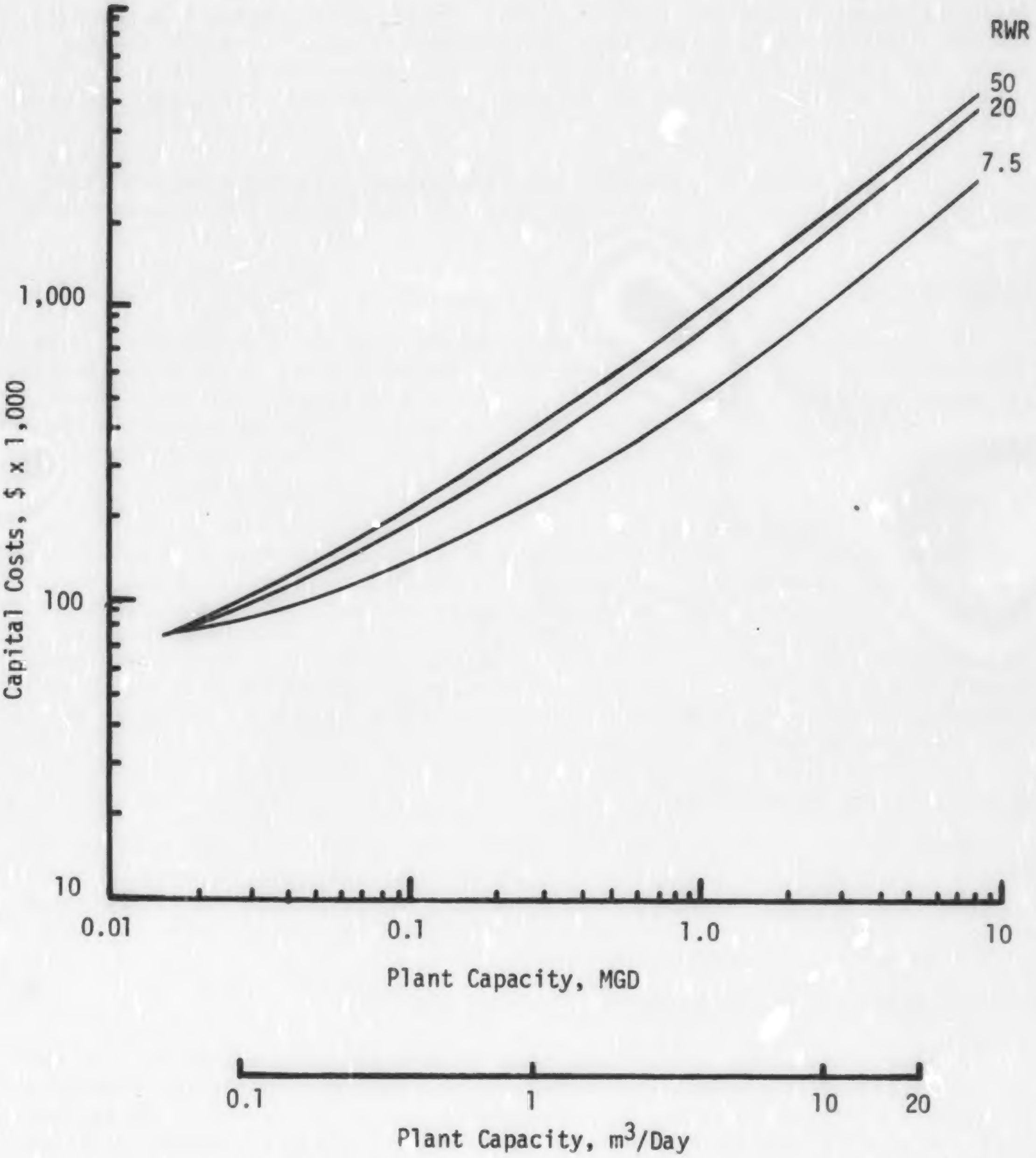


FIGURE 47. CAPITAL COSTS OF REVERSE OSMOSIS TREATMENT

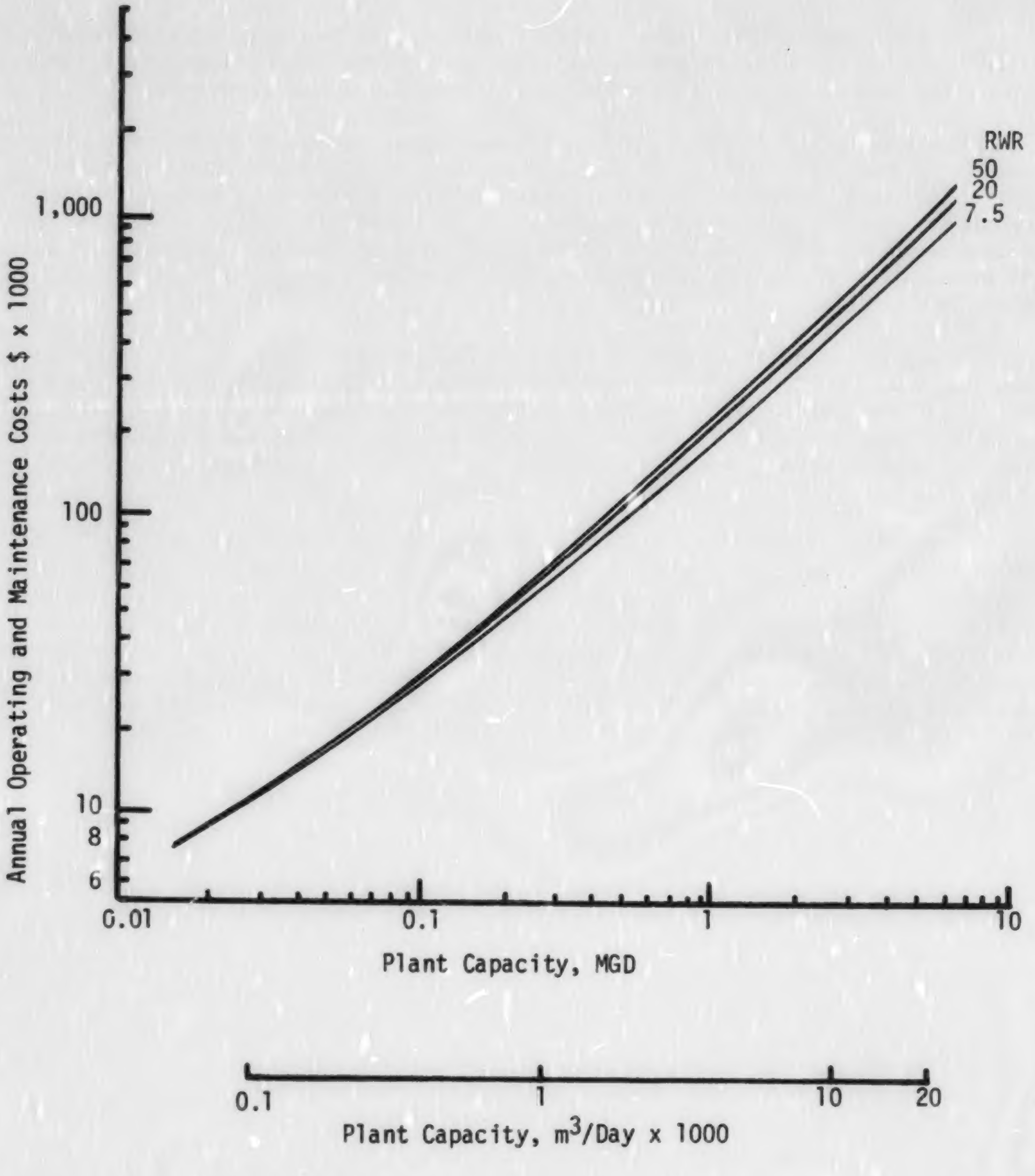


FIGURE 48. ANNUAL OPERATING AND MAINTENANCE COSTS, REVERSE OSMOSIS TREATMENT

BRINE DISPOSAL COSTS

Several methods for brine disposal were considered for detailed calculations: lined evaporating ponds, pipeline and transmission, subsurface injection, and treatment as a nuclear waste. Assumptions and curves follow.

Costs of brine disposal by lined evaporating ponds assumed a net evaporation of five feet per year[26] and a land cost of $1850 per acre. Capital costs included land, construction, vinyl lining, engineering design, and contingency. Operation and maintenance costs included all labor, including payroll extras and overhead, as well as supplies and repair of equipment. Figure 49 summarized the unit costs for different radium concentrations and total dissolved solids.

Costs of brine transmission to an outfall assumed one mile of pipeline and one pumping station.[26] Outfall costs were considered negligible. Capital costs included pipeline, pumping station, and right-of-way costs. Operating and maintenance costs included power labor and overhead. Figure 50 summarized the final unit costs as a function of radium concentration and total dissolved solids.

Subsurface injection costs were calculated with basic assumptions[26] of 3000 ft depth, well head pressure of 500 psi, an aquifer permeability of 135 millidarcies, and a porosity of 5 percent. Capital costs included wells, well field distribution system, pumping station, storage, engineering and design, interest during construction, and contingency. Not included were environmental impact assessments required by many states. Operation and maintenance costs included power, supplies, labor and overhead. Figure 51 indicates the unit costs for different radium concentrations and total dissolved solids.

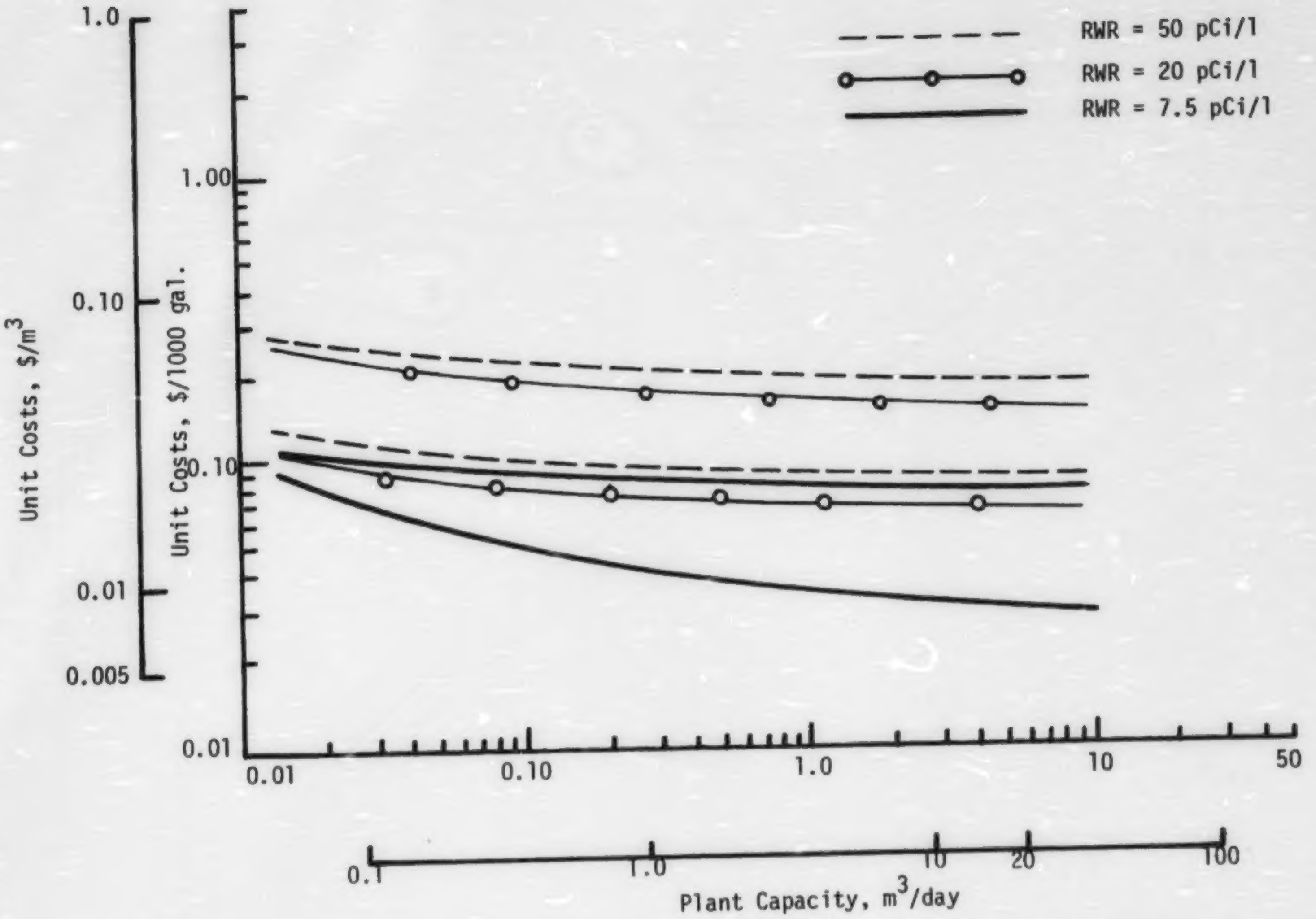


FIGURE 49. UNIT COST OF WASTE DISPOSAL BY LINED EVAPORATING PONDS, REVERSE OSMOSIS

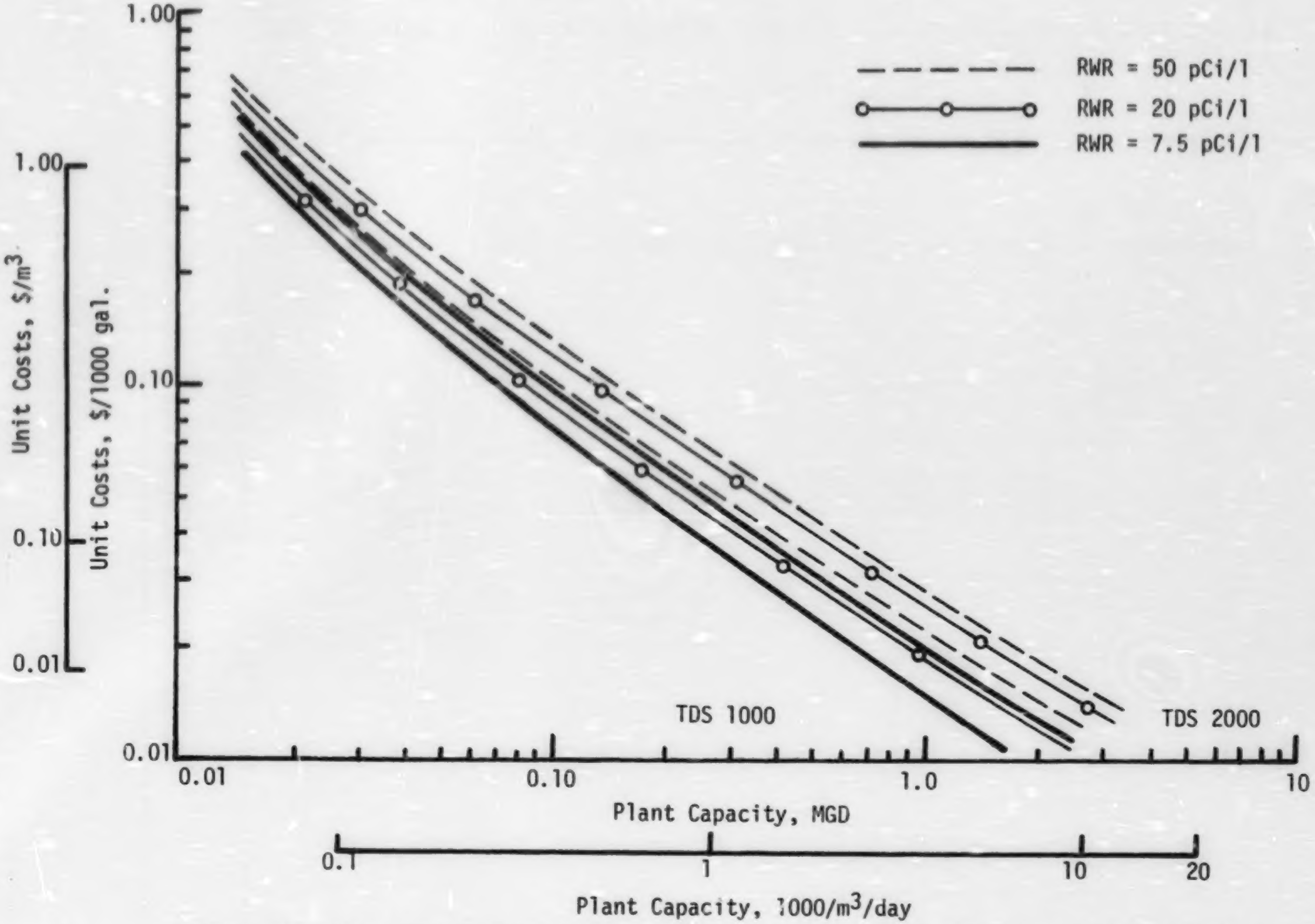


FIGURE 50. UNIT COST OF WASTE BRINE TRANSMISSION PER MILE OF PIPELINE, REVERSE OSMOSIS

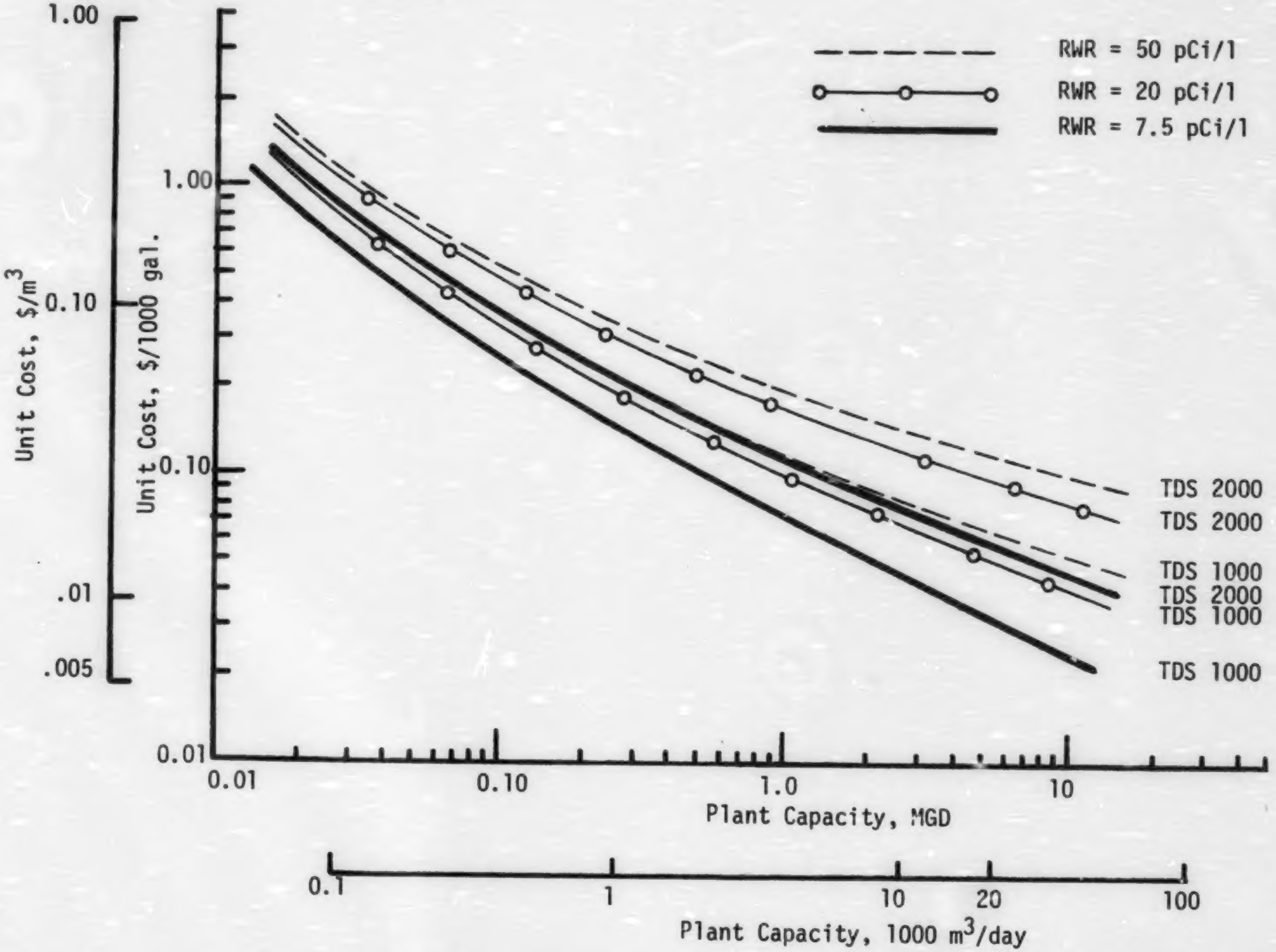


FIGURE 51. UNIT COST OF WASTE DISPOSAL BY SUBSURFACE INJECTION: REVERSE OSMOSIS

SECTION IX

UNIT COST CURVES

Unit cost curves for each process have been developed as a function of raw water radium activity and total solids. Unit cost curves for RWR = 7.5 pCi/l, RWR = 20 pCi/l, and RWR = 50 pCi/l are presented respectively in Figures 52 through 54. These curves are based on the following conditions:

40-year plant life (20 years for ion exchange and reverse osmosis)
8 percent interest rate

These curves are intended for use as a preliminary estimate only. Any conditions different from the above listed conditions or those conditions listed in the cost determination section will materially affect these curves. It can be seen from these figures that the ion exchange process offers the lower unit cost of water treated to remove radium to the 5.0 pCi/l limit, except at high solids levels when the RWR is 20 or greater. The lime-soda process offers the lower unit cost under these conditions.

The lime-soda process is quite cost effective for the entire range of conditions, particularly for plant capacities over 10 MGD.

Reverse osmosis offers the highest unit cost. It is expected that reverse osmosis will be limited to applications in which the raw water quality is quite brackish or where the RWR is quite high.

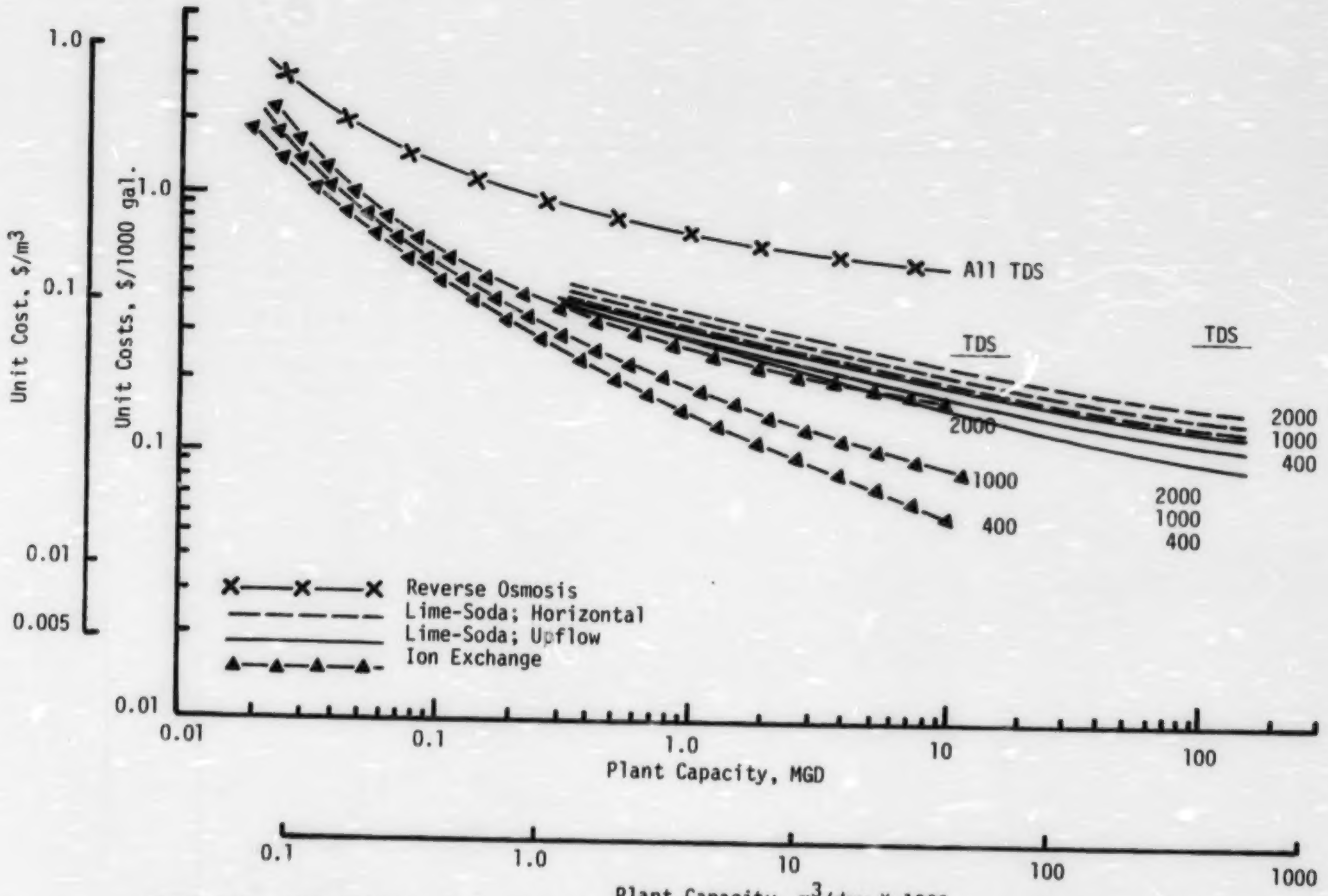


FIGURE 52. COMPARISON OF UNIT COSTS OF WATER TREATMENT. WASTE DISPOSAL COSTS EXCLUDED, TO MEET RADIUM STANDARD OF 5.0 pCi/1 FOR RWR = 7.5 pCi/1.

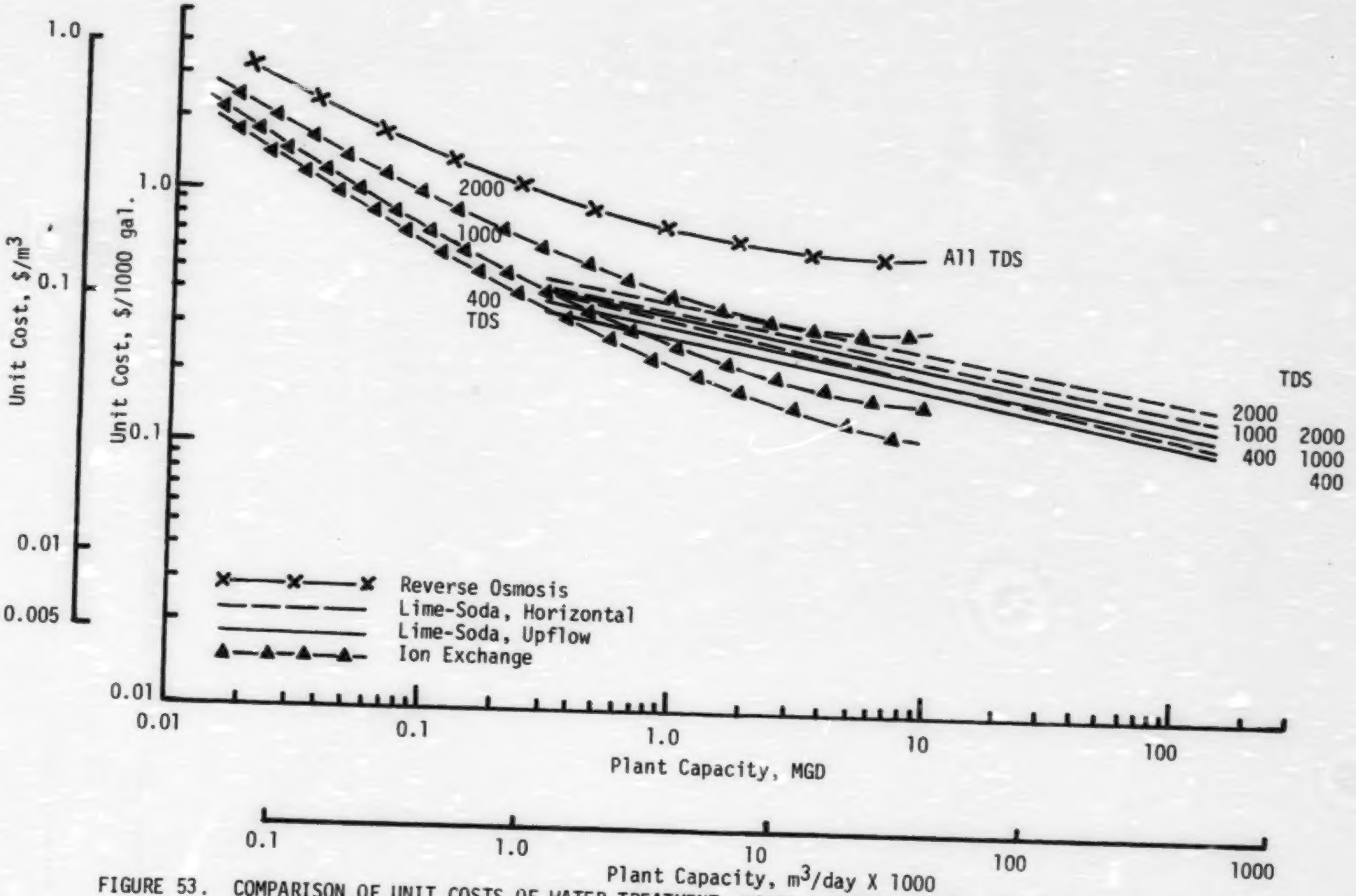


FIGURE 53. COMPARISON OF UNIT COSTS OF WATER TREATMENT, WASTE DISPOSAL COSTS EXCLUDED, TO MEET RADIUM STANDARD OF 5.0 pCi/1 FOR RWR = 20 pCi/1.

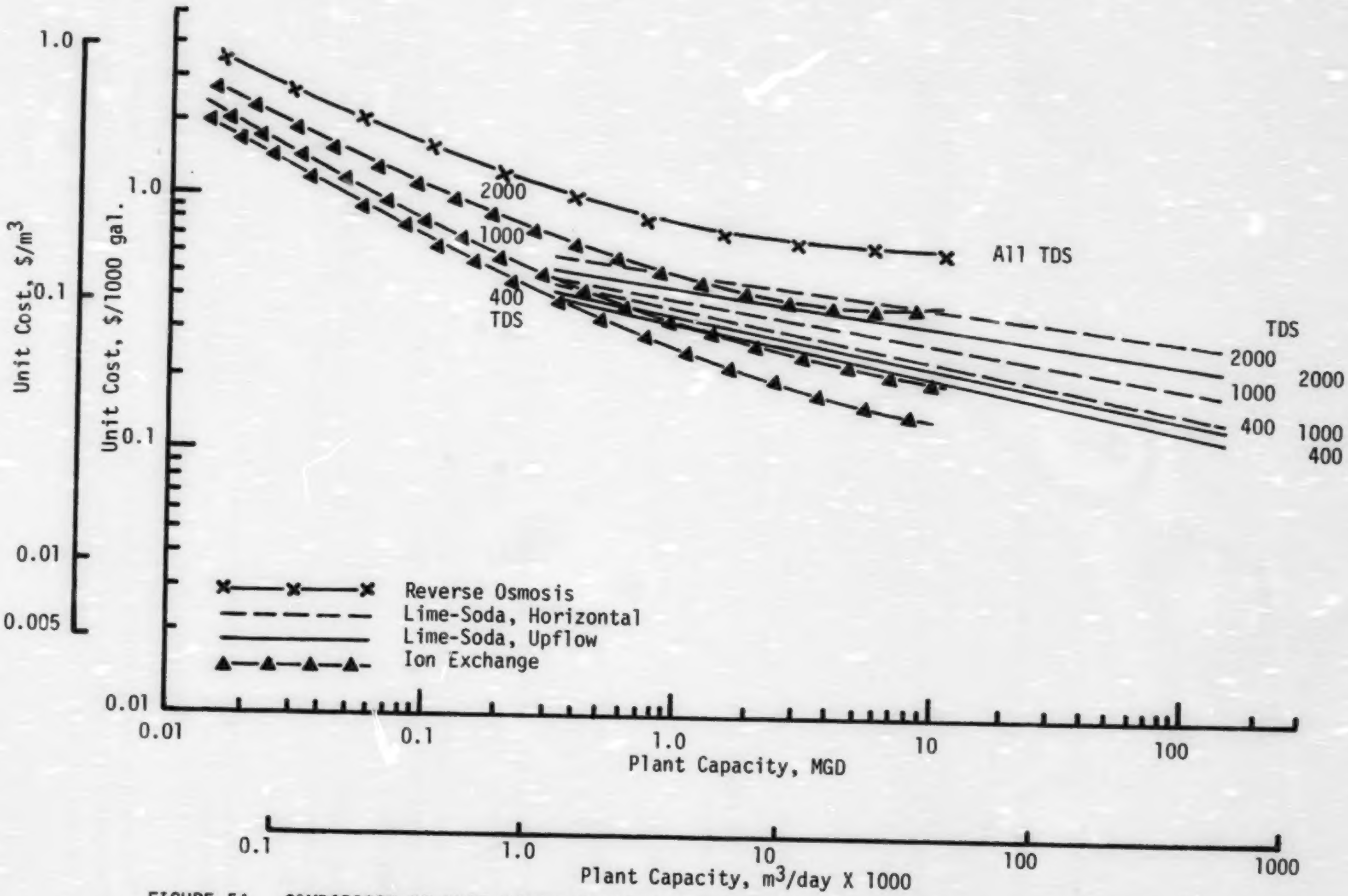


FIGURE 54. COMPARISON OF UNIT COSTS OF WATER TREATMENT, WASTE DISPOSAL COSTS EXCLUDED, TO MEET RADIUM STANDARD OF 5.0 pCi/l FOR RWR = 50 pCi/l.

SECTION X

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ANNUAL COST SHEET

PROJECT:

PROJECT DESCRIPTION:

K. ANNUAL OPERATING COSTS:	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
O&M LABOR, SUPPLIES & MAINTENANCE MATERIAL 8.			
9.			
10.			
11.			
FUEL 12.			
13.			
STEAM 14.			
15.			
ELECTRIC POWER 16.			
CHEMICALS 17.			
ANNUAL REPLACEMENT COSTS 18.			
OTHER ANNUAL COSTS 19.			

L. TOTAL ANNUAL COSTS

M. DEPRECIATING CAPITAL COST (ANNUAL BASIS)

N. NON-DEPRECIATING CAPITAL (ANNUAL BASIS)

O. TOTAL ANNUAL CAPITAL CHARGES

P. TOTAL ANNUAL COSTS (SUM ITEMS L, O)

Q. COST OF WATER ($\$/m^2$)

CAPITAL COST SHEET

PROJECT:

PROJECT DESCRIPTION:

DATE: ____________

PRICE LEVEL: ____________

PLANT CAPACITY: ____________

ANNUAL PRODUCTION: ____________

INTEREST RATE: ____________

PLANT LIFE: ____________

WATER SUPPLY CHARACTERISTICS:

PRODUCT WATER CHARACTERISTICS:

A. CAPITAL COST CENTERS:	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
1.			
2.			
3.			
4.			
5.			
6.			
7.			

B. SUBTOTAL ------------------------------------

C. INTEREST DURING CONSTRUCTION ------------------------------------

D. START-UP COSTS ------------------------------------

E. OWNERS GENERAL EXPENSE ------------------------------------

F. TOTAL DEPRECIATING CAPITAL (SUM B, C, D, E) ---------

G. LAND COSTS ------------------------------------

H. WORKING CAPITAL ------------------------------------

I. TOTAL NON-DEPRECIATING COSTS ------------------------

J. TOTAL CAPITAL COSTS ------------------------------------

COMPUTATION SHEET

PROJECT:

PROJECT DESCRIPTION:

ANNUAL FUEL COSTS:

ANNUAL STEAM COSTS:

ANNUAL POWER COSTS:

ANNUAL REPLACEMENT COSTS:

ANNUAL CHEMICAL COSTS:

LAND REQUIREMENTS:

OTHER COMPUTATIONS:

APPENDIX B

SAMPLE CALCULATIONS

Lime-Soda Process

High Solids Raw Water

TH - 750 mg/1 @ $CaCO_3$
Ca^{++} - 500 mg/1 @ $CaCO_3$
Mg^{++} - 250 mg/1 @ $CaCO_3$
ALK - 300 mg/1 @ $CaCO_3$
TDS - 2000 mg/1
CO_2 - 11.4 mg/1 @ $CaCO_3$

1 - Desired finished water for Ra_0 = 7.5 pCi/1
Ra removal required - 33 percent or .33
TH removal required - $Ra_{rem}^{2.86}$
$= .33^{2.86} = .042$
Minimum TH considered practical in lime-soda process is 35 percent

TH removal required = .35 (750) = 262 mg/1 @ $CaCO_3$, or 5.25 mg/1
TH of finished water= 488 mg/1 @ $CaCO_3$ or 9.75 mg/1

2 - Chemical requirements

Parameter	Raw		Finished	Δ	Required CaO	Required CaO
	mg/1	mg/1	meq/1	mg/1	meq/1	meq/1
CO_2	5	0.23	0	0.23	0.23	-
Ca^{++}	200	10.00	4.75	5.23	5.25	-
Mg^{++}	60	5.00	5.00	0	-	-
HCO_3	366	6.00	0	6.00	0.75	-
TOTALS					6.23	

$$\text{Lime Required} = \frac{(6.23)(28)}{.90} = 194 \text{ mg/1}$$

Soda Ash Required = None

CAPITAL COST SHEET

PROJECT:
Lime-Soda Softening Plant 3.0 MGD (11,360 m^3/Day)

PROJECT DESCRIPTION:

Conventional Plant with
Rapid Sand Filtration

DATE:
PRICE LEVEL: October 1, 1975
PLANT CAPACITY: 3.0 MGD (11350 m^3/day)
ANNUAL PRODUCTION: 4,145,000 m^3
INTEREST RATE: 8%
PLANT LIFE: 40 yrs.

WATER SUPPLY CHARACTERISTICS:
Ra_o = 7.5 pCi/l
High Solids

PRODUCT WATER CHARACTERISTICS:

A. CAPITAL COST CENTERS: Source: David Volkert & Assoc.	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
1. Plant Construction (Basins)	$330,000	1351/1137	$ 392,100
2. Plant Construction (Filters)	$300,000	1351/1137	356,500
3. Site Development (Basins)	$250,000	1351/1154	292,700
4. Site Development (Filters)	$ 70,000	1351/1154	81,950
5.			
6.			
7.			

B. SUBTOTAL--	$1,123,250
C. INTEREST DURING CONSTRUCTION 1 yr @ 8% of B --------	89,900
D. START-UP COSTS----------- 1/12 of L -----------	16,275
E. OWNERS GENERAL EXPENSE-- 12% of B -------------	134,800
F. TOTAL DEPRECIATING CAPITAL (SUM B, C, D, E)---------	$1,364,200
G. LAND COSTS--	4,200
H. WORKING CAPITAL-------- 1/6 of L ----------------	32,600
I. TOTAL NON-DEPRECIATING COSTS----------------------	36,800
J. TOTAL CAPITAL COSTS-------------------------------	$1,401,000

ANNUAL COST SHEET

PROJECT:
Lime-Soda Softening Plant 3.0 MGD (11,360 CMD)

PROJECT DESCRIPTION: Conventional Plant with Rapid Sand Filters; $Ra_o = 7.5$ High Solids

K. ANNUAL OPERATING COSTS: *	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
O&M LABOR, SUPPLIES & MAINTENANCE MATERIAL 8. Labor and Other O&M Costs			$153,000
9.			
10.			
11.			
FUEL 12. N/A			
13.			
STEAM 14. N/A			
15.			
ELECTRIC POWER 16. N/A			
CHEMICALS 17. Lime	$42,300		$42,300
ANNUAL REPLACEMENT COSTS 18. N/A			
OTHER ANNUAL COSTS 19. N/A			

L. TOTAL ANNUAL COSTS	$195,300
M. DEPRECIATING CAPITAL COST (ANNUAL BASIS) 0.0839 (1,364,200)	114,500
N. NON-DEPRECIATING CAPITAL (ANNUAL BASIS) 0.08 (36,800)	3,000
O. TOTAL ANNUAL CAPITAL CHARGES	117,500
P. TOTAL ANNUAL COSTS (SUM ITEMS L, O)	$312,800

Q. COST OF WATER ($\$/m^2$) 312,800 ÷ 4,145,000 cm = $\$.075/m^3$ or $.286/1000 gal

*Source: Compilation of Personal Correspondence of Authors

APPENDIX C

Ion Exchange

1 - Mass Balance Calculation

To determine fraction of raw water influent blended, and fraction treated, assuming 95 percent removal in I/E or R/D column.

For mass balance of Ra:

$$.05\ Ra_o x + Ra_o\ (1-x) = (1)(5)$$

$$.05\ Ra_o x + Ra_o - Ra_o x = 5$$

$$x\ Ra_o\ (.05 - 1) + Ra_o = 5$$

$$-.95\ x\ Ra_o = 5 - Ra_o$$

$$x = \frac{5-Ra_o}{-.05\ Ra_o}$$

$$x = \frac{Ra_o - 5}{.95\ Ra_o}$$

Blending allowed to attain minimum level of 5 pCi/l Ra assuming 95 percent Ra removal in I/E and R/O

Ra Level	Fraction Blended	Fraction Blended
50	.053	.947
20	.211	.789
7.5	.649	.351

2 - Regenerant Chemicals Calculations

Assume:
1) operating capacity of resin = 20 kgr hardness as $CaCO_3$/CF
2) regeneration is with a 10 percent brine concentration
3) salt required for regeneration is 0.30 lb salt/kgr hardness as $CaCo_3$ removed (6 lb salt/CF)
4) 95 percent TH removal in unit (5 percent leakage)

Solids Levels:

High - $TH_{raw} = 750$, $TH_F = .05\ (750) = 37.5$

$$TH_{rem} = 712.5\ \text{mg/l}$$

Kilograins hardness removed

$$\frac{712.\ 5\ \text{mg/l}\ \ 1\ \text{grain/gal}\ \ \text{k kgr}}{17.1\ \text{mg/l}\ \ 1000\ \text{g}} = .0417\ \text{kgr/gal}$$

Salt regeneration requirement/MG

$$\frac{.0417 \times 10^6\ \text{kgr}\ \ .30\ \text{lb salt}}{\text{mg}\qquad\qquad \text{kgr}} = 12{,}510\ \text{lb}$$

Volume of rinse water/MG, assume 30 gal/CF resin

$$\frac{41{,}700\ \text{kgrTHr}\ \ \text{CF}\ \ 30\ \text{gal}}{\text{mg}\qquad 20\ \text{kgr}\quad \text{CF}} = 62{,}550\ \text{gal}$$

Volume of regeneration brine solution/MG

$$\frac{12{,}510}{.10} - 12{,}510 = 112{,}590\ \text{lb}\ H_2O$$

$$13{,}500\ \text{gal}\ H_2O$$

Total volume of backwash + rinse water/MG

High Solids - 13,500 + 62,550 = 76,050 gal or 7.6 percent of total flow

COMPUTATION SHEET

PROJECT:

Lime-Soda Softening Plant 3.0 MGD (11,360 CMD)

PROJECT DESCRIPTION:

Conventional Plant with Rapid Sand Filters

Ra_o = 7.5 High Solids

ANNUAL FUEL COSTS:

Included in Line 8

ANNUAL STEAM COSTS:

Included in Line 8

ANNUAL POWER COSTS:

Included in Line 8

ANNUAL REPLACEMENT COSTS:

Included in Line 8

ANNUAL CHEMICAL COSTS:

Lime -
$$\frac{1610\ \text{lb}}{\text{MG}} \left| \frac{3\ \text{MG}}{\text{Day}} \right| \frac{365\ \text{Days}}{\text{yr}} \left| \frac{\text{Ton}}{2000\ \text{lb}} \right| \frac{\$45}{\text{Ton}} = \$42{,}310$$

LAND REQUIREMENTS:

Mixers and Basins
5 ha @ $750 = $3750
.5 ha @ $750 = 375
$4125 say $4200

OTHER COMPUTATIONS:

ANNUAL COST SHEET

PROJECT:
Ion Exchange 0.5 MGD

PROJECT DESCRIPTION: $Ra_o = 7.5$
TDS = 400

K. ANNUAL OPERATING COSTS:	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
O&M LABOR, SUPPLIES & MAINTENANCE MATERIAL 8. Overhead and Maintenance	$13,000	7.28/6.25	$15,100
9.			
10.			
11.			
FUEL 12.			
13.			
STEAM 14.			
15.			
ELECTRIC POWER 16.			
CHEMICALS 17.	$3,200		$3,200
ANNUAL REPLACEMENT COSTS 18.			
OTHER ANNUAL COSTS 19.			

L. TOTAL ANNUAL COSTS	$18,300
M. DEPRECIATING CAPITAL COST (ANNUAL BASIS) .10185 (152,300)	15,500
N. NON-DEPRECIATING CAPITAL (ANNUAL BASIS) .08 (1700)	100
O. TOTAL ANNUAL CAPITAL CHARGES	15,600
P. TOTAL ANNUAL COSTS (SUM ITEMS L, O)	33,900

Q. COST OF WATER ($\$/m^2$) $\$33,900/690,800\ m^3 = \$.049/m^3$ or .186/1000 gal.

CAPITAL COST SHEET

PROJECT: Ion Exchange 0.5 MGD (1892 m^3/day)

PROJECT DESCRIPTION:

Actual Treated Flow = 667 m^3/day

DATE:

PRICE LEVEL: October 1975

PLANT CAPACITY: 0.5 MGD (1892 m^3/day)

ANNUAL PRODUCTION: 690,800 m^3

INTEREST RATE: 8 percent

PLANT LIFE: 20 years

WATER SUPPLY CHARACTERISTICS:

Ra_o - 7.5

TDS - 400

PRODUCT WATER CHARACTERISTICS:

A. CAPITAL COST CENTERS: Source: David Volkert & Assoc.	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
1. Plant Construction	$73,000	1351/1137	$86,700
2. Site Preparation	$37,000	1351/1154	$43,300
3.			
4.			
5.			
6.			
7.			

B. SUBTOTAL	$130,000
C. INTEREST DURING CONSTRUCTION 6 mos @ 8% per year = 4% of B	5,200
D. START-UP COSTS 1/12 x item L	1,500
E. OWNERS GENERAL EXPENSE 12 percent of B	15,600
F. TOTAL DEPRECIATING CAPITAL (SUM B, C, D, E)	152,300
G. LAND COSTS 125 ha @ $750 =	200
H. WORKING CAPITAL	1,500
I. TOTAL NON-DEPRECIATING COSTS	1,700
J. TOTAL CAPITAL COSTS	$154,000

APPENDIX D

Reverse Osmosis Calculations

1 - Assumptions

High Solids - Initial $TDS_i = 2000$ mg/l

Product $TDS_i = .05\ (2000) = 100$ mg/l

Calcium initial, $Ca_i = 200$ mg/l

2 - Brine to Product Ratio (BPR) =

$$BPR = \frac{1 - (TDS_p/TDS_i)}{(900/Ca_i) - 1}$$

$$BPR = \frac{1 - (100/2000)}{(900/200) - 1} = \frac{.95}{3.5} = .271$$

3 - Brine Volume (V_b)

$V_b = V_p \times BPR = .271\ V_p$ V_p = Product Volume

4 - Feed Volume (V_i)

$V_i = V_p + .271\ V_p = 1.271\ V_p$

CAPITAL COST SHEET

PROJECT:
Reverse Osmosis 0.5 MGD (1892 m^3/day)

PROJECT DESCRIPTION:

Actual Treated Flow

667 m^3/day

DATE:
PRICE LEVEL: October 1975
PLANT CAPACITY: 0.5 MGD, 1892 m^3/day
ANNUAL PRODUCTION: 690,800 m^3
INTEREST RATE: 8 percent
PLANT LIFE: 20 years

WATER SUPPLY CHARACTERISTICS:

Ra_o 7.5; TDS 400

PRODUCT WATER CHARACTERISTICS:

A. CAPITAL COST CENTERS: Source: David Volkert & Assoc.	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
1. Plant Construction	$185,000	1351/1137	$220,000
2. Site Development	38,000	1351/1154	44,000
3.			
4.			
5.			
6.			
7.			

B. SUBTOTAL	$264,000
C. INTEREST DURING CONSTRUCTION	11,000
D. START-UP COSTS	8,000
E. OWNERS GENERAL EXPENSE	32,000
F. TOTAL DEPRECIATING CAPITAL (SUM B, C, D, E)	315,000
G. LAND COSTS negligible	--
H. WORKING CAPITAL	8,000
I. TOTAL NON-DEPRECIATING COSTS	8,000
J. TOTAL CAPITAL COSTS	$323,000

ANNUAL COST SHEET

PROJECT: Reverse Osmosis 0.5 MGD (1892 m^3/day)

PROJECT DESCRIPTION: Ra_o = 7.5 TDS = 400

K. ANNUAL OPERATING COSTS:	ESTIMATED COST	COST INDEX	CURRENT ESTIMATED COST
O&M LABOR, SUPPLIES & MAINTENANCE MATERIAL 8.	$12,000	7.28/6.25	$14,000
9.			
10.			
11.			
FUEL 12.*			
13.			
STEAM 14.*			
15.			
ELECTRIC POWER 16.*			$86,000*
CHEMICALS 17.*			
ANNUAL REPLACEMENT COSTS 18.*			
OTHER ANNUAL COSTS 19.*			

L. TOTAL ANNUAL COSTS	$100,000
M. DEPRECIATING CAPITAL COST (ANNUAL BASIS) (.10185) (315,000)	32,000
N. NON-DEPRECIATING CAPITAL (ANNUAL BASIS) .08 (8,000)	1,000
O. TOTAL ANNUAL CAPITAL CHARGES	33,000
P. TOTAL ANNUAL COSTS (SUM ITEMS L, O)	$133,000

Q. COST OF WATER ($/$m^2$) $133,000/609,000 = $.218/$m^3$ or $.826/1000 gal.

*$125 per 1000$m^3$ production covers all items indicated.

APPENDIX E

In the main body of the report it was stressed that the reported costs of treatment and waste disposal for removal of radium to the proposed interim standard were for entirely new construction. Many water utilities have existing facilities which, with treatment process improvements and/or minor construction of additional facilities, can effectively meet the radium standard.

As an illustrative example, let us assume that three water utilities utilize a raw water with the same chemical characteristics as the medium solids water described earlier in this report. The chemical quality of this water is then:

TDS	1,000 mg/1
TH	300 mg/1 as $CaCO_3$
Ca^{++}	200 mg/1 as $CaCO_3$
Mg^{++}	100 mg/1 as $CaCO_3$
Alk	200 mg/1 as $CaCO_3$

Let us assume further that the radium level of the raw water is 50 pCi/1 and that all three plants have a design capacity of 3.0 MGD.

The three water plants have the following existing facilities:

Plant A - Chlorination only
Plant B - Conventional horizontal flow lime softening unit followed by rapid sand filtration. Lime (CaCO) is used without soda ash at a dose of 125 mg/1 resulting in a finished water TH of 100 mg/1
Plant C - Ion exchange softening and blending of 30 percent raw water to obtain a finished water TH of 100 mg/1 as $CaCO_3$

In order for utility A to meet the proposed interim standard of 5.0 pCi/1 entirely new treatment facilities must be constructed and the cost to the utility would be that obtained from the cost curves presented in this report and summarized below:

Utility A decides to construct an upflow solids contact lime-soda softening unit with rapid sand filtration.
Capital costs are estimated from Figure 4 to be $1,000,000.
Annual operating costs are estimated from Figure 14 to be $200,000 per year.
Unit costs of treatment are estimated from Figure 54 to be approximately $.30/1000 gallons.
Sludge disposal will be handled by a temporary sludge thickening lagoon at a unit cost of $.01/1000 gal from page 52 followed by transportation by truck to a nearby landfill at a unit cost of approximately $.02/1000 gal for transport from Figure 17 and $.15/1000 gal for landfilling the thickened sludge from Figure 19.

Total unit cost of the new system is then:

Treatment	\$.30/1000 gallons
Disposal	\$.18/1000 gallons
Total	\$.48/1000 gallons

Utility B is presently removing 66 percent of raw water TH. The actual amount of radium removal should be determined by radiochemical analysis, but for illustrative purposes Figure 3 can be used to estimate the finished water radium level at 6.8 pCi/l. In order to remove radium to 5 pCi/l, 90 percent of RWR must be removed corresponding 74 percent TH removal (also from Figure 3). The finished water TH must be equal to or less than 78 mg/l as $CaCO_3$. This can be achieved by the addition of approximately 55 mg/l more lime and 55 mg/l soda ash. Simple jar jests can be used to verify required chemical doses estimated for additional hardness removal. The additional chemical doses will cost the utility:

$$\frac{55\ \text{mg/l CaO} \times 834\ \text{lb/MG} \times 3\ \text{MGD} \times 365\ \text{days} \times \$98}{\text{mg/l} \qquad\qquad \text{Year}\ \ 2000\ \text{lb}} =$$

\$12,050/year Lime

$$\frac{55\ \text{mg/l}\ Na_2CO_3 \times 8.34\ \text{lb/MG} \times 3\ \text{MGD} \times 365\ \text{days} \times \$\ 87}{\text{mg/l} \qquad\qquad \text{Year} \qquad\qquad 2000\ \text{lb}} =$$

\$21,849/year Na_2CO_3

Total Annual Additional Cost = \$46,462
Total Unit Cost Addition = \$.04/1000 gal

In order for Plant C to remove radium to 5 pCi/l, 94.7 percent of the raw water must be treated, from Figure 24 or simple mass balance assuming 5 percent leakage of radium. Since the plant is currently treating only 70 percent of the raw water, the increase in treated water fraction amounts to (.947 - .700)(3 MGD) = .74 MGD which must be treated.

Assuming that the present unit is operating at full design capacity, an additional ion exchange unit (or units) must be added to handle the increase in water to be treated. The design capacity of the additional units will then be .75 MGD.

From Figure 31, the capital cost of plant expansion will be approximately \$470,000.

From Figure 34, the increased annual operating and maintenance costs will be approximately \$60,000 per year.

From Figure 54, the unit cost of the water produced by the additional treatment facilities will be approximately \$.37/1000 gallons, assuming that presently existing brine disposal facilities will be adequate. Assuming the present unit cost of water treated by Plant C is $.15/1000 gallons, proportioning the unit cost of the expanded facilities gives a new unit cost estimate of $.21/1000 gallons. The resulting increase in unit cost necessary to meet the radium standard of 5.0 pCi/1 then is $.06/1000 gallons.

The above example demonstrates that three similar size utilites treating similar water ranged from $.04/1000 gallons to $.48/1000 unit cost required for meeting the radium standard of 5.0 pCi/1.

APPENDIX F

1. CALCULATIONS:

According to Burgess and Niple

14,000 gal of 4% sludge could be used per acre of Ohio farmland in order to increase the pH of 5.9 to the desirable range. It has also been calculated that 5×10^3 pCi/kg of Ra -226 can be obtained in 4% sludge ($\rho \sim 1$).

$$14{,}000 \text{ gal/acre} \times 3.78 \text{ liter/gal} \equiv 53{,}000 \text{ liter/acre.}$$

$$53{,}000 \text{ liter/acre} \times 5 \times 10^3 \text{ pCi/liter} = 2.65 \times 10^8 \text{ pCi/acre}$$

$$2.65 \times 10^8 \text{ pCi/acre} \times \frac{1 \text{ acre}}{4.37 \times 10^4 \text{ ft}^2} = 6.05 \times 10^3 \text{ pCi/ft}^2$$

Assuming a mixing depth of 6"

$$6.05 \times 10^3 \text{ pCi/ft}^2 \times 2 = 12.1 \times 10^3 \text{ pCi/ft}^3 \text{ for the top 6"}$$

Assuming no uptake by vegetation or weathering loss,

$$1.21 \times 10^4 \text{ pCi/ft}^3 \times \frac{1 \text{ ft}^3}{28.3 \text{ liter}} \begin{array}{l} = 4.27 \times 10^2 \text{ pCi/liter} \\ = 4.27 \times 10^{-1} \text{ pCi/gm.} \end{array}$$

Now: $.2 \text{ pCi/gm} \Rightarrow .0005 \text{ WL}$

$$Y = .4 \, \frac{(.0005 \text{ WL})(.427)}{.2} \equiv .00044 \text{ WL.}$$

Note: Correction factor ($\sim .4$)

Therefore, in 25 years, you would exceed .01 WL in worst possible case. However, this is only WL.

Worst possible case is that which would exist only if this quantity was added to the site every year and there is no uptake by vegetation or weathering effects.

2. CALCULATIONS:

Using "EPA models" and in-house data we know the following:

(1) ~ 17 μR/hr (estimated α) .01 WL (internal structure)

(2) ~ 1.2 μR/hr (external α) .0002 WL

(3) 1 WL = 10^2 pCi/liter of Rm 10^{-2} WL = 10^3 pCi/m^3 of Rn
(definition)

(4) $\phi = 1.6\ C_{Ra-226}$ in soil pCi/m^2 - sec where

(a) C_{Ra-226} is conc. in pCi/gm;

(b) ϕ is the radon flux from soil.

(5) $C = 155\ \phi$ (assumption of EPA model)

Assume C_{Ra-226} soil = 1 pCi/gm.

$C = 155\ \phi \quad 155 \times 1.6$ pCi/m^3 of Rn ~ 2.5×10^2 pCi/m^3 Rn.

$$2.5 \times 10^2 \text{ pCi/m}^3 \times \frac{10^{-2} \text{ WL}}{10^3 \text{ pCi/m}^3 \text{ Rn}} \quad 2.5 \times 10^{-3} \text{ WL}$$

Thus 0.01 WL = 4 pCi/gm of Ra in soil.

Now 4 pCi/gm = 4×10^3 pCi/kg Highest 4% sludge radium concentration.